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DEPARTMENT OF NAVAL ARCHITECTURE
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13. ABSTRACT

Experiments intended to shed light on the mechanism of the capsizing of an intact ship in heavy seas are described. These experiments were carried out in San Francisco Bay using a radio controlled model of a cargo liner. Three capsizing modes were observed: low cycle resonance, pure stability loss, and broaching. All modes are seen to be strongly influenced by the effect of quartering or following seas in attenuating the ship's stability. Some conclusions are reached concerning the value of such experiments in predicting minimum stability standards.

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EXPERIMENTAL STUDIES OF CAPSIZING
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November 1972

DEPARTMENT OF NAVAL ARCHITECTURE
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I. INTRODUCTION

An investigation into the survivability of an intact ship in heavy seas entails the study of extreme motions of ship and wave where nonlinear hydrodynamic phenomena are important and where the event of central interest, capsizing, has a low frequency of occurrence. By its very nature, therefore, such a study would not be expected to be amenable to the linearized procedure which has proven so successful in attacking problems of performance and average behavior (motions, stresses, sustained speed) in average sea states.

Several methods have been used in the past for studying nonlinear phenomena in ship motions. They include rational methods of solution of the nonlinear differential equation of motion, numerical integration of the differential equations (numerical simulation), analog simulation and model experiments. The rational methods may be expected to have two useful features. They permit the extension of solutions obtained by the linear techniques to more severe seaways and motion regimes, and they may reveal certain phenomena such as motion instability, which are not apparent from a linearized analysis. Most such techniques, however, still entail making certain idealizations which limit their usefulness in predicting such extreme features of behavior as capsizing.

The numerical and analog simulations depend for their accuracy upon several factors. The foremost of these is the ability of the investigator to recognize the essential characteristics of the phenomenon and to properly model it through appropriate numerical or electronic means. Assuming an accurate numerical model or analog circuit representation, the accuracy of the results is influenced by numerical errors such as round-off, convergence, and stability in the former case, or electronic noise, drift, and other circuit imperfections in the latter.

Model experiments hold the possibility of most closely simulating the characteristics of the real ship. The principal mechanical limitations here are those imposed by scale effects and the degree of accuracy with which the model and its equipment represents the real ship, and of course, the closeness of simulation of the real sea environment. A more fundamental question concerns the usefulness of the results, particularly the question of how one extrapolates the results of a single test or group of tests to other ship forms or other sets of conditions than those prevailing at the time of the test. This latter may impose the most severe limitations on the applicability and usefulness of model testing. The first two limitations may usually be overcome through the expenditure of sufficient effort. Thus, by using a model of sufficient size, scale effects may be made acceptably small and, at the same time the model instrumentation, for example, the automatic steering mechanism with which the model must certainly be equipped, can be made to accurately represent the ship characteristics.

There remains the question of properly representing the seaway, for which two possibilities exist: artificially generated waves in a seakeeping basin, or natural wind generated waves on a lake or bay. The principal advantages of open water versus laboratory wave basin testing are as follows:

(a) There is the possibility of obtaining more realistic (short crested) and severe seas than can be generated artificially.

(b) Longer model runs are possible, thus yielding a larger statistical sample of the performance. This is especially important in following or quartering seas which are the most important in capsizing studies.

(c) The capital investment in laboratory facilities may be less.

The difficulties inherent in open water testing include:

(a) Lack of control of the sea environment, thus an inability to preset the test conditions of the seaway for any particular experiment.

(b) Logistical difficulties in transporting, launching, and recovering models and wave measuring equipment.

(c) External disturbances from shipping traffic, tidal currents, and changes in wind and sea during an experiment.

Both the value and difficulties of such open water experimentation have been amply demonstrated by the work carried out during recent years by the group working under the direction of Professor Wendel of the Universities of Hamburg and Hanover. It is not the present purpose to summarize earlier work, but nevertheless, it is certainly in order to acknowledge the contributions of the above group.

Encouraged by the success of Wendel's group, several other laboratories have undertaken to perform model experiments to study capsizing in heavy seas. Part of the impetus for this work stems from the nature of the criteria upon which the judgment of stability has traditionally been based. In the past such criteria have been derived from long experience with ships which are, for the most part, similar in size, proportions, and speed. It may be expected in the future, however, that such features of new ships will change substantially, the changes taking place so rapidly that it is no longer possible to extrapolate design criteria from previous experience. With this in mind, a research program involving

model experiments in open water has been initiated at the Department of Naval Architecture of the University of California, Berkeley, under the sponsorship of the U. S. Coast Guard.

The immediate goal of these experiments is to simulate, in model scale, the behavior of a ship operating in a heavy seaway, with particular emphasis on the conditions of loading, course, and speed which result in a high probability of capsizing. During these experiments, recordings are made of the seaway and certain parameters describing the model motion. These are later analyzed statistically in order to obtain quantitative measures of the sea and model performance. The behavior of the model is also recorded by means of motion pictures with especial effort made to capture on film events such as broaching, capsizing, loss of control and other potentially dangerous situations.

These model experiments have resulted in a reasonably thorough understanding of the phenomena by which a ship finds itself endangered in a heavy seaway. They cannot, however, be expected to provide the sole basis for formulating stability criteria for new ships since, in effect, they merely serve as a substitute for past experience. In this sense, the model experiments are even inferior to real experience with real ships since they cannot be expected to cover as extensive a range of ships, sea, and operating conditions, nor as long a time span as necessary. The first function of the experiments, instead, may be viewed as providing basic insight and understanding of the endangering phenomena. On the basis of this understanding, a theoretical simulation procedure will then developed which is sufficiently versatile to permit its application to the wider variety of ships and situations for which predictions are sought. The second function of the model tests is to provide quantitative data for proving the theoretical simulation after it has been developed. The two, experiments and theoretical simulation,

are seen, therefore, to be complementary to each other. The experiments provide the basic understanding and quantitative proof upon which the simulation is based and the simulation provides a means of extrapolating the limited experience represented by the model experiments to the wide variety of real situations. It is the purpose of this paper to describe the model experiments and to give some of the conclusions which have been reached to date, on the basis of the experimental data and observations.

II. APPROACHES TO THE PROBABILITY OF CAPSIZE

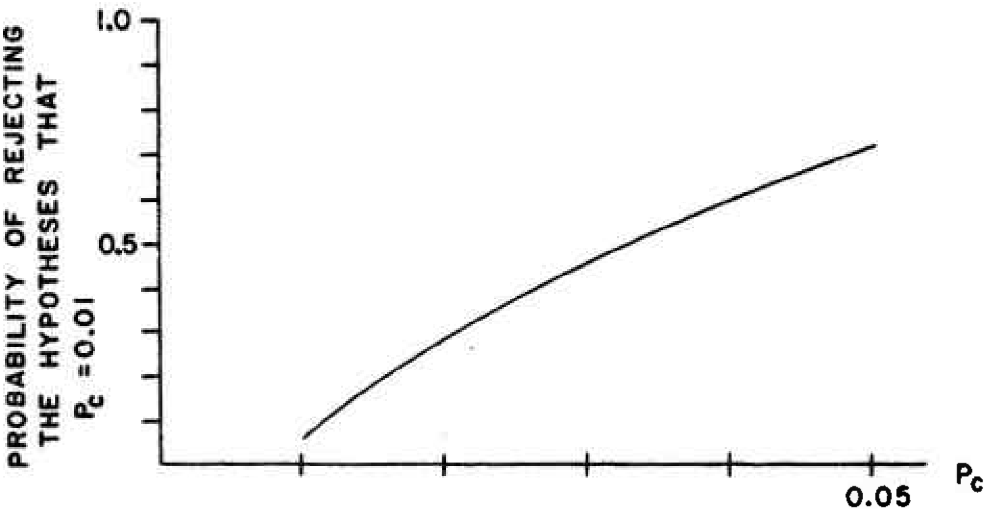
Ship safety from capsize is a probabilistic concept. In the last analysis, to say that a ship will not capsize intact is to say that the risk of capsize is negligible. Thus, in orienting our test program towards determining the minimum stability to prevent capsizing we have considered the requirements for testing data in a probabilistic framework.

One approach to the probability of capsizing has not proven fruitful in the context of the experiments. This approach is performing tests of significance based on the frequency of model capsizings or constructing confidence intervals on the basis of the number of capsizes in an experiment of a given number of runs. The tests can be performed and the intervals estimated but they do not yield useful conclusions.

To explain this we can consider a point estimate of the order of probabilities of intact capsize that ship owners face. Give or take a few dozen, there are 5,000 ships of greater than 5,000 gross tons operating in a given year. On the average, the number of intact capsizings is about one. The order of magnitude for the probability of capsize, $\hat{P}_c$, for the "average" ship is then $1/5000 = 2 \times 10^{-4} = \hat{P}_c$ in any year. Hence the probability of avoiding loss from capsize in a 20-year lifetime is $(1 - \hat{P}_c)20 \doteq .996$. This estimate does not change significantly for any $\hat{P}_c$ in a 98% confidence interval about $\hat{P}_c$. The experimental task is to determine what characteristics of a ship guarantee this order of safety from capsize, or even greater safety. In this context it is important to recall that one model run, which may be considered one binomial trial, has a duration of 15 minutes on model scale, or about 90 minutes on ship scale.

Now suppose we attempted to ascertain low probabilities of capsize from the observed proportion of capsizes from total

runs by using the traditional methods of hypothesis testing. Suppose, for the sake of easy calculation, we were willing to accept probabilities of capsizing in one model run as high as 0.01 (50 times greater than $\hat{P}_c$). Then the evidence required for Type I error avoidance at the 95% level would be no more than one capsize in 50 or 75 runs, two in 100 runs.[1] The "power of the test" to discriminate between the hypotheses (1) that the probability of capsize is 0.01 and (2) that it is some other value, varies with the level of alternate values of the true probability of capsize.[2] If the true probability of capsize is 0.05, the power of the test in an experiment of 50 runs is only 0.72; for the true probability of capsize equal to .03 the power of the test is a meager 0.45.



The power of the one tailed test for P_c=0.01 with a confidence level of 0.95, based on 50 runs.

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1 Type I error is rejecting a hypothesis when it is in fact true. In this case the hypothesis is that the probability of capsize is less than or equal to 0.01.

2 The "power of the test" is the probability of rejecting a false hypothesis. To say the "power of the test" is 0.72, is the say that there is 1-0.72=28% chance a false hypothesis would be accepted.

In this hypothetical case of 0.01 probability of capsize, the hypothesis testing approach would leads us to design the experiment in hope of getting only one capsize in each 50 runs, and even then the resolution of the probability estimates, the power of the test, would be poor. Moving to the order of probabilities approaching those for actual ships would lead to experimental programs in which no capsizings occur.

In sum, where the order of probability is so low and the requirements for resolution of the estimates so high, one must have an enormous data base for making probability estimates. The model experiments themselves cannot provide the data base. However, wave records may, and as we arrive at a better understanding of the mechanics of capsize we will be analysing the wave data gathered from oceanographical observations with a view towards determining the low probabilities of the occurrence of waves which will mechanistically induce capsizing of an intact ship.

III. PHILOSOPHY OF EXPERIMENTS AND EQUIPMENT

The capsizing of a ship in a seaway may be thought of as the result of two factors: the forces and moments acting on the ship which tend to cause her to capsize, and the ability of the ship to withstand those forces, i.e., her stability. Both of these factors vary with time as the ship moves in a seaway and depend on ship geometry, speed, heading, and sea severity. The capsizing forces come from external and internal sources such as the wind, waves, and rudder. The stability, measured by the curve of righting moments versus heel angle, is a function of ship geometry and load distribution for a ship in calm water. In a seaway, however, the relative position of ship on the waves has a very strong effect on stability.

In considering questions of survivability this influence of the seaway on transverse stability is of particular importance since, for certain, not unrealistic positions of ship relative to wave, the transverse stability may vanish altogether even though the ship is judged to have adequate stability in calm water. The effect of waves on transverse static stability has been studied especially by Arndt and Roden (1958) and Paulling (1958), (1961). In general, if one considers a ship operating in a following or quartering sea, it is shown that the righting arms are reduced below the calm water values when the crest of a wave is near amidships and increased above the still water values when a trough is near amidships. The reduction of righting arms is much more severe for a ship with low freeboard than for one with high freeboard, and, for sufficiently steep waves, the righting arms may vanish over the entire normal calm water range of stability.

The effects of this wave-induced righting arm variation are twofold. First, if the stability reduction in the crest is sufficiently great and is experienced for a sufficiently

long time, the ship may capsize statically. This would occur, for example, if the ship is running before a steep following sea at a speed about equal to the phase velocity of the waves, and remains on the crest of a particularly steep sea for a sufficient period of time. Second, an unstable resonant rolling motion may develop when the ship, again operating in quartering or following seas, encounters the waves at certain frequencies. This unstable motion, which is primarily a result of the wave-induced periodic variations in stability rather than periodic exciting moments, is termed parametrically induced motion and has been studied by Grim (1952), Kerwin (1955), and Paulling and Rosenberg (1959). The essential feature of parametrically induced instability is that it can exist in the absence of a periodic exciting moment, i.e., in a pure following sea. If an external moment, in addition, exists, the phenomenon is exaggerated, leading to extreme rolling motion building up very quickly with increased possibility of capsizing. In such a situation both the exciting moment and the stability variations excited by the waves play important roles in the behavior, and neither can be ignored.

The steering mechanism of the ship represents another source of external force input and, in general, may be though of as a closed loop control system involving either a man or autopilot in its feedback branch. Such a system, in which we have a response in the form of rudder activation to a stimulus in the form of heading error, suggests the possibility of a kind of resonant behavior of the combined yaw-roll-steering system. Under especially severe sea conditions, this may lead to severe roll and yaw motion and a degraded ability to control the ship. A description of such a roll-yaw-control system coupling observed in practice has been given by Taggart (1970).

From the above discussion it is apparent that several factors must be considered in a model testing program intended

to reveal the basic nature of ship capsizing in a severe seaway. First, the model must possess the essential ship features which influence the phenomenon. This is obtained by constructing the model in such a way that it properly scales the geometry and weight distribution of the ship, and equipping it with propulsion and steering systems which possess the ship characteristics. In addition, the model must be equipped with systems for sensing and recording the important performance parameters. Second, it is necessary that the wave condition in which the experiments are conducted represent reasonably well the severe sea states in which ship operation is to be simulated. Apparatus must then be provided for measuring and recording the sea conditions at the time of the experiments.

For the present experiments, a model of the American Challenger class of cargo ships was used. A body plan of the model is shown in Figure 1. A 1/30 scale model of this ship having a length between perpendiculars of 5.35 meters already existed and was made available to the project. This model was considered especially suitable for three reasons. First, it represented a standard type of cargo liner typical of a large number in service, therefore typical of ships which form the basis for "experienced-based' stability criteria. Second, it was of a suitable size to contain the necessary instrumentation and was large enough to be reasonably free of scale effects. Third, and most important, the scale was such that sea conditions to be expected in the proposed testing area would represent severe full scale sea conditions. This is discussed further in a later section. For these initial experiments the model was not equipped with superstructure and rigging since the objective was primarily to investigate hydrodynamic effects.

The model was fitted with five systems of equipment and instrumentation:

1. A main propulsion system consisting of a permanent magnet D.C. motor supplied by a closed loop speed regulation system. This system was designed to maintain constant average motor RPM under varying loads.

2. A steering system which incorporated provision for either manual or autopilot control. The latter included adjustable heading and rate sensitivity, an adjustable dead band, and adjustable steering engine speed (rudder rate). Autopilot parameters could, therefore, be adjusted to closely simulate the response of the ship autopilot.

3. A four-channel motion sensing and recording system comprising roll-pitch-yaw gyroscopic outputs plus rudder angle. These were recorded by means of a four track analog tape recorder installed in the model.

4. A five-channel radio link for transmitting various on-off, control, calibration, and manual steering signals to the model.

5. A power supply consisting of a bank of rechargeable leak-proof batteries which provide power for main propulsion motor, gyroscopes, tape recorder, and other functions.

The experimental operation was conducted and monitored from the 35-foot long catamaran research ship, Froude-Kriloff, which was especially constructed for this purpose. This craft has equipment for lifting and transporting the model and wave buoy, an electronic equipment area, and a raised navigation bridge.

During a typical experiment, the model displacement, radii of gyration and metacentric height are adjusted to represent a specific condition of loading of the ship. With

the model still aboard the catamaran, the autopilot gyroscope is brought up to speed and then uncaged when the catamaran is on the desired model course relative to the seas. The model is then launched, the propulsion motor started, and after the autopilot brings it onto the predetermined course, the tape recorder is started.

In general, the length of run is adjusted to permit recording about 200 wave encounters if the model does not capsize first. Attention was concentrated on beam, quartering, and following sea conditions where the danger of capsizing is greatest. Motion picture records are made of representative runs, particularly those in which capsizing is expected. These are usually made at high camera speed so that when later projected at low speed, the time scale will be nearer that of the ship.

The wave conditions in the test area are obtained by means of an array of four step-resistance wave gages supported by a tension-leg buoy. The outputs of these gages are recorded in analog form on four track magnetic tape using a tape recorder on board the catamaran which is anchored nearby during wave recording sessions. It is seen, therefore, that waves are not recorded simultaneously with the model experiment nor at the exact moving location of the model. Rather, the average conditions in the vicinity of the model are obtained and the measurement is repeated several times during the testing day. The average conditions at the time of an individual test are then obtained by interpolation.

At the conclusion of a day of testing, the model motion tapes and wave record tapes are taken ashore where equipment is available for analog-to-digital conversion. Records are digitized, calibration factors are applied, and the digital data on computer compatible tapes are taken to the University's computer center for further processing. This processing takes

two forms, standard time-series analysis (spectral analysis) and direct statistical processing of maxima, zero crossings, and other features.

IV. EXPERIMENTAL WAVE CONDITIONS

It is obviously important, in order for the model test results to have any resemblance to reality, that the sea conditions in the test area must resemble the full scale conditions of interest. To some extent, however, the full scale conditions which one wishes to simulate are not well documented since extreme conditions occur infrequently in nature. Neither is it completely clear just what conditions should be duplicated. That is, do we wish to study the severe seasonal storm conditions which ships will be likely to encounter during a small but consistent period of the year or do we wish to study conditions more severe than those which most ships may encounter once or not at all during their entire lifetime. To some extent, this question of the conditions to be simulated is closely tied in with the question of the acceptable degree of risk. That is, if it is accepted that no ship can be made perfectly safe against casualty, only that the risk can be held below some small and, hopefully, predictable probability, we must the decide what constitutes an acceptable probability.

A major unknown factor in assessing the degree of risk of capsize to which a ship is exposed is the maximum severity of the seaway which she will encounter. In the 1967 ISSC Committee report on environmental conditions by Hogben (1967), some famous extreme waves are described. The dimensions of these extreme waves are usually based on visual observation and contain, therefore, a great deal of uncertainty. Waves of 14 to 34 m height are mentioned. The same report, as well as the 1970 ISSC report by the same committee, contain tabulations of long term sea state observations by weather ships in the North Atlantic. These indicate that sea states having significant wave heights exceeding 9.5 meters prevail generally between one-half and one percent of the time during the worst season of the year. Such a sea state is probably

representative of the worst which a ship operating in that area has any reasonable probability of encountering during any single year.

Some initial wave measurements in the proposed model testing area on San Francisco Bay had indicated that seas of significant height 0.2 to 0.3 meter could be expected during a substantial number of days in the summer. At a model scale of 1/30, these represent seas 6 to 9 meters high. This is within the range of sea states which prevail in the North Atlantic of the order of ten percent of the winter season. Figure 2 is a histogram of significant wave heights actually measured during the 1971 summer testing season which bears out the earlier predictions of wave heights.

The 9.5 meter height mentioned above corresponds to 1.04 feet to the scale of Figure 2 and, therefore, it appears that these experiments were conducted in sea states representing the most severe ten percent of the time in the North Atlantic with some approaching the worst 0.5 percent.

Aside from the severity of the seaway as measured by significant wave heights, it is important that the frequency distribution of the model and full scale waves bear a general resemblance to each other. This is best judged from a comparison of the respective spectra. A good recent tabulation of spectra obtained from a North Atlantic weather ship equipped with a Tucker wave meter is given by Miles (1971). One is struck at first by the great variability in shape of these "real" spectra, but this variability is also discussed in the aforementioned ISSC committee reports. Spectra of all of the wave measurements made during our model experiments in 1971 are given in the report by Haddara, et al (1972). Two examples of model spectra from that report are reproduced in Figures 3 and 4. Superimposed on them are spectra taken from Miles (1971) but reduced to the model scale. These equivalent full scale spectra were chosen to have peaks located

at about the same (scaled) frequency and scaled significant heights approximately equal to those of the respective model spectra.

The full scale and model spectra are seen to agree quite well. In fact, the overlap is well within the 95 percent confidence bands of either of the spectra. Although only two examples, chosen at random from the measured model spectra, are given here, a comparison of these two with the other model spectra reveals that they are typical of all of the model spectra. There appears to be a much greater variability, in fact, in the shapes of the full scale spectra.

From this, it is concluded that the seas in the model testing area are representative of some quite severe full scale conditions that have been measured at sea. The latter show great variation in the spectral shapes and, therefore, the model test conditions may not cover all realistic sea conditions, even of the same degree of severity as measured by, e.g., significant height. This serves to emphasize the statement made in the Introduction that the model experiments cannot, by themselves, cover the entire range of ship experience. They can, however, represent a reasonable sample of real experience, thereby providing a basis for analysis and extrapolation by mathematical means.

V. FEATURES OF CAPSIZINGS OBSERVED IN EXPERIMENTS

The discussion presented here will be entirely confined to results obtained during the summer of 1971 since, at the time of writing, the processing of 1972 data is still in progress. During 1971, a total of 132 experiments were conducted and the model was observed to capsize 22 times. All of these capsizes occurred in quartering or following seas although 15 of the experimental runs were in beam seas.

The conditions in which the model was tested are given in Table I. Basically, the experiments were made at two displacements, light and heavy, and for each displacement a range of GM's, speeds, and course headings relative to waves were investigated. The speed tabulated here is the speed in still water at the propeller RPM of the experiment. The speed in waves will generally be less than this value, but, in a following or quartering sea, the difference in speed due to added resistance is not substantial.

Figures 5 and 6 show the righting arm curves for the two displacements. The model was equipped with ballast weights which could be shifted vertically to permit adjustment of the GM. On these figures, the label "Position of the ballast weight" which appears on the right hand axis refers to the discrete positions of these movable weights. Thus, these graphs may be used to obtain the righting arm curves for any particular condition of ballasting of the model. Curves of righting arms for the ship in a longitudinal wave are also plotted. The wave length is equal to ship length and the height is taken as 1/17.9 times the length.

The longitudinal radius of gyration of the model was adjusted to 0.25 L in the light condition and 0.27 L in the heavy. The transverse radii of gyrations were 0.38B and 0.34B respectively, with slight variations in these figures for different positions of the movable ballast.

All of the experiments conducted during 1971 are summarized in Table II. Runs resulting in capsizing are marked by an "X" in this table. For this tabulation, the sea conditions at the time of the test have been divided into three categories: "Low" refers to seas with a significant height below 0.6 ft. (18.3 cm); "High" refers to a significant wave height above 0.8 ft. (24.4 cm); and "Medium" lies between these two limits. The numerical identifiers listed in the table, i.e., 4.01, 8.09, etc. are a labelling code used for identifying the experiments and cataloging the data stored on magnetic tapes.

The first feature which one notices after looking over this table is that only one capsize occurred in the light, high freeboard condition, and that at high speed in following seas of medium height. The GM in this case, was substantial and would normally be considered adequate for the ship. The nature of this capsize will be discussed in more detail later. In the heavy condition, all capsizes occurred in following or quartering seas, and all at GM values less than that of the single light displacement capsize. This latter merely serves to emphasize the point that the sample size, i.e., number of runs in any given condition, is too small to allow any hard conclusions to be drawn regarding minimum required stability. Rather, these experiments were planned to screen a large range of parameters in order to isolate those cases of most interest for further more detailed study in our pursuit of understanding of the capsizing phenomenon.

As noted above, all capsizes occurred in following or quartering seas, and these, as were pointed out in an earlier section, are the headings of ship relative to waves in which the stability is most strongly affected by the waves. From observing the capsizes and the motion picture records of them, it was clear that the attenuation of stability by the waves played a very important role in nearly all capsizes. Further,

it was possible to distinguish three distinct modes of capsizing which may be described as follows.

Mode 1: Low Cycle Resonance.

This refers to an oscillatory rolling motion which builds up rapidly, i.e., in two to five cycles, to a very large amplitude, culminating in a capsize. The appearance of the roll motion record is similar to the motion of a linear oscillating system being excited by a frequency near its natural frequency where the superposition of a transient and a steady state motion results in the existence of "beats".

In the present case, the phenomenon appears to occur in approximately the following sequence. The model, while operating in following or quartering seas, encounters a group of especially steep and regular waves. When the crest of a wave is about amidships, the stability of the model is greatly reduced and it takes a large roll. This wave moves on past the model and a trough comes into the amidships position while the model is heeled over, resulting in sharply increased stability. This causes the model to "snap" back upright, acquiring a high roll angular velocity by the time it reaches the upright position. Another wave crest, meanwhile, is moving into the amidships position, resulting in diminished stability once again as the ship starts rolling past upright and to the other side. The ship then rolls far over to that side against a diminished restoring moment. If now another trough moves into the amidships position with the correct timing, the roll will be stopped and the model snaps upright again. This process continues until either the model capsizes or it moves out of the wave group and the motion dies down. The capsize occurs if the angular momentum of the model at the upright position of the roll is sufficient to carry it beyond the angle of zero righting arm as it rolls into the next crest. It appears almost as if the suddenly increased righting arm experienced by the sharply heeled model in the

trough position tends to catapult it over to the other side into the soft and yielding embrace of the next crest.

The essential characteristic of this mode of capsize is a very regular rolling motion which, in a group of three or four waves, grows rapidly to a large amplitude. It usually occurs at a frequency of one-half the wave frequency, therefore at the first Mathieu resonant frequency as discussed by Grim (1952) and Paulling and Rosenberg (1959). It was, however, sometimes observed to occur at a frequency equal to the encounter frequency, especially in quartering seas. This is the frequency of the rolling moment exerted by the seas on the model but it is also the second Mathieu resonant frequency. In either case, however, the rolling motion builds up rapidly and capsizing occurs as the model rolls into a wave crest.

Mode 2: Pure Loss of Stability

This usually occurs in a following sea at high speed. The model is observed to encounter one or more very steep and high waves and, with little or no preliminary rolling motion, simply loses all stability when a crest moves into the amidships position and "flops" over. The essential prerequisite for this to occur is a model speed nearly equal to the wave phase velocity so that the model remains almost stationary relative to the crest for a sufficient length of time to capsize. The necessary wave would be of about the same length as the model and the height would be sufficient to immerse the deck in the crest with the model upright. This, of course, implies a high model speed since a Froude number of 0.4 is required for the model speed to be exactly equal to wave speed in waves of length equal to model length. From motion picture records of several capsizes of this nature, it appeared that a model speed lying between the group velocity (one-half the phase velocity) and the phase velocity could result in this mode of capsize.

Mode 3: Broaching

This is the most dynamic mode, in appearance and has received the most attention in the previous literature. A good descriptive summary of several full scale experiences of broaching is given by Conolly (1972). In this mode of capsize, the model is struck from astern by three or four steep breaking seas in succession. As each wave strikes it, the model is forced to yaw off course to such an extent that the steering system is unable to correct the heading in the time interval between waves. The breaking seas striking the model, combined with the dynamic heeling moment resulting from the turn, combine to cause capsizing, again with the crest of a wave amidships. The essential features of broaching are the breaking waves striking the model in series, and the large heading deviation and associated angular velocity.

On several occasions, broaching was observed to occur without capsizing but with such total loss of directional control that the model swung through ninety degrees from a following sea course to beam seas. This was observed most frequently in the light displacement condition where the rudder was less deeply immersed and therefore less effective. On one such occasion, at low speed, the model was totally unable to regain its original course, but remained in the beam sea condition even with the rudder hard over. The only capsize which occurred in the light condition of the model was a result of broaching.

While these modes of capsize are most dramatically and clearly recorded by means of motion pictures, some of their distinguishing features may be observed in the time history records of rolling motion and in the motion spectra.

We shall consider here only a few typical examples of motion records and associated spectra intended to illustrate

the modes of capsizing described above. Two figures are given to illustrate each case. The first is a plot containing normalized spectra of roll, pitch, and waves. Recall that the wave measurement was made at a fixed location in the test vicinity and, in general records were made before and after, but not simultaneously with a model run. In most of these figures, therefore, two wave spectra are plotted, one from the nearest wave record taken before and the other after the model run. The second figure of each pair shows time history plots of the roll, pitch, yaw, and rudder motions respectively.

It would have been desirable to measure the waves at the model location and time, in addition to the fixed location measurement, but a satisfactory means of accomplishing this is yet to be developed. It is found, however, that the pitch response relative to wave slope of the model operating in following or quartering seas is nearly unity for waves longer than about one and one-half model lengths, dropping off for shorter waves to about one-half at a wave length equal to model length. The pitch spectrum, therefore, may be considered to give some indication of the wave slope encounter spectrum but with attenuation of the higher frequency components.

All plotted spectra have been normalized such that the integral equals one. The variance or spectral area, m_o, however, is tabulated for each case, and from this, the average values of the respective motions may be obtained.

A characteristic of the transformed spectrum for seas approaching the model abaft the beam is a singular behavior at a certain frequency. This may be illustrated heucristically as follows and the details may be found in, e.g., St. Denis and Pierson (1953). The encounter frequency, f_e, for a ship moving at an angle X to the waves is

$$f_e = \frac{c}{\lambda} - \frac{U \cos \chi}{\lambda} = f(1 - \frac{2\pi}{g} fU \cos \chi), \tag{1}$$

where c = wave velocity = $g/2\pi f$,

U = model velocity,

$f = \sqrt{g/2\pi\lambda}$,

and λ = wave length.

The wave energy contained in a narrow frequency band, df, must be the same in fixed and moving coordinates after transformation of the frequency. This is expressed by

$$S_e(f_e)df_e = S(f)df \quad .$$

Therefore, the transformed spectral density, $S_e(f_e)$, is given by

$$S_e(f_e) = \frac{S(f)}{(dfe/df)} = \frac{S(f)}{1 - \frac{4\pi f U \cos \chi}{g}} \quad . \tag{2}$$

The denominator vanishes, and $S_e(f_e)$ becomes infinite at a frequency

$$f_e^* = g/(4\pi U \cos \chi) \quad . \tag{3}$$

The corresponding frequency in fixed coordinates is obtained by substituting (3) back into equation (1),

$$f^* = 2f_e^* \quad . \tag{4}$$

Physically, this merely means that the wave energy which is concentrated in a narrow band of frequencies centered about f^* will be encountered by the ship as a much narrower

band of frequencies centered about f_e^*, i.e., the ship's forward speed compresses the spectrum into a narrower frequency band in the vicinity of f_e^*. If the peak of the spectrum lies in the vicinity of f^* there exists, therefore, the possibility of the ship encountering a group of very large and regular waves at encounter frequency f_e^*. This depends further, of course, on the component waves being in phase with each other at the time the ship encounters them.

Let us now consider several example experimental records and examine them in the light of the foregoing discussion. Figures 7 through 10 show two experiments run with identical model conditions illustrating broaching. In the first, the model capsized after going out of control three times during the course of the run. In the second, the model went completely out of control, broached and changed heading by ninety degrees but did not capsize. The losses of control are shown in the records of yaw and rudder motion in Figure 8 at about 62, 182, and 350 seconds by the chopped off signals caused when the yaw motion reached the limit of its scale and the rudder reached its stops. Similar saturation of signals is shown in Figure 10 centered at 62 seconds and the complete loss of control at about 360 seconds. The latter was filmed in its entirety and in the films it was seen that the model was struck by four successive breaking waves, causing it to roll far to port (down wave) and yaw further to starboard with each wave. The group of waves then passed on after the model had turned ninety degrees, allowing it to recover and return to course.

If we assume that the pitch record represents reasonably well the encounter slope spectrum and that the model rolls primarily in response to waves near its natural roll frequency, the graphs of spectra, Figures 7 and 9, indicate that the peak exciting frequency nearly coincides with the roll natural frequency. The average rolling motion amplitudes are

similar in the two ca... but are slightly greater in the latter case where the pitch and roll peaks are more nearly in coincidence.

The next example shown in Figures 11 and 12 illustrates capsizing mode 1, low cycle resonance. Two features may be distinguished which are characteristic of the motion leading up to this mode. The peak frequencies of the motion spectra in roll and pitch are in the ratio 1/2, i.e., roll occurs predominantly at a frequency of one-half the pitch, therefore, wave frequency. The same characteristic is observable in the motion records themselves, Figure 12. Note also, in the latter figure, the beat nature of the roll record and especially the build up of roll immediately prior to the capsize.

A pure loss of stability capsize, mode 2, is shown in Figures 13 and 14. Note that the roll spectrum is rather broad, indicating no pronounced resonant response, and the mean amplitude of roll is quite small. The motion record, Figure 14, shows no beats or resonance build up in contrast to the previous example in Figure 12. Both this capsize and the previous, low cycle resonance capsize, were recorded on film. While the model behavior in the previous case very clearly showed the rapid build up of roll motion to catastrophic amplitude in the three or four cycles prior to capsize, the present record showed virtually no roll in two or three waves before the capsize. This last very steep wave then slowly overtook the model, and when the crest was near amidships, the model quickly capsized to port. Perhaps the most significant feature of the motion prior to this capsize is the complete lack of any discernible pattern.

The next example shown in Figures 15 and 16 was a broaching capsize in the heavy condition. The motion prior to capsize shows some of the features of low cycle resonance, i.e., beats and short periods when the roll motion for

several cycles occurs at one-half the encounter frequency. Neither of these effects is so pronounced as in the example shown in Figures 11 and 12, nor is the capsize itself associated with any distinct features of the motion record. In this case, the motion picture record shows a single large wave breaking under the counter and throwing the stern violently around. The wave moved on forward as the model slewed around and again, capsizing occurred with the breaking crest near amidships.

The last two examples are, again, nearly identical cases, and are in fact, successive runs, one of which resulted in a capsize and the other of which did not. In this case, the model was given an initial list of ten degrees to port and the resulting asymmetry results in a small rolling moment acting even in a pure following sea. The interesting feature of the spectra in this case is the relation of the singular transformed frequency to the peak of the wave spectrum. The transformed singular frequency, f_e^*, is seen to occur at just about the peak of the pitch and roll response spectra and the corresponding frequency in fixed coordinates, f^*, at the peak of the wave spectrum. This means that the wave components having maximum energy, i.e., those grouped around the peak of the wave spectrum, are compressed into a much narrower band of encounter frequencies grouped around f_e^*, which is apparently near the resonant roll frequency. The motion records in these two cases show very regular roll and pitch motion with distinct beats in the records. The capsize shown in Figure 18 is of the low cycle resonant nature, building up in about three oscillations from nearly zero to capsizing.

VI. CONCLUSIONS

The purpose of this paper is to present a progress report on a research program intended to study the capsizing of intact ships in heavy seas. The results obtained to date have aided greatly in the development of understanding of the mechanism of capsizing and have defined certain areas on which future work will be focussed. The work has not yet progressed to the point that specific recommendations may be made concerning acceptable stability limits but some conclusions may be stated as follows:

1. Capsizing of an intact ship in following and quartering seas occurs by one of three modes: low cycle resonance, pure loss of stability, and broaching, with the first predominating.

2. All three modes, but especially the first two, are strongly influenced by the attenuation of stability which the ship experiences when a wave crest is amidships.

3. It is infeasible to expect to base stability standards solely on the results of capsizing experiments because the sample size is too small to provide adequate significance to the results for even one ship configuration.

4. The best hope for formulating a probabilistic basis for stability standards is to develop a thorough understanding of the mechanism of capsizing as it relates to ship-wave characteristics. On this basis, capsizing can be related to the occurrence of certain ship-wave relationships, whereupon ocean wave statistical information may then be used to predict the probability of the ship encountering such critical configurations.

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Table I: Data for the Full-Scale Ship at Mcdel Test Conditions

	Light Displacement			Heavy Displacement		
Length between perpendiculars, m	158.84					
Beam - molded, m	22.87					
Depth amidships, m	14.18*					
Displacement, tons S.W.	12,086			19,652		
Mean Draft, m	6.10			9.07		
Freeboard Amidships, m	8.08			5.11		
Metacenter above Baseline, m	9.36			9.56		
Speed - calm water knots	13	19	23	13	16.5	20
Froude Number	0.17	0.25	0.30	0.17	0.22	0.26
GM/B (Range) percent	-0.087 to 2.73			0.342 to 2.36		

*Depth of actual ship was 12.96 m but model was constructed to top of bulwark amidships.

Table II: Summary of Conditions - 1971 Experiments

Light Model Displacement Condition

HEADING			FOLLOWING			QUARTERING			BEAM		
Wave Height Cond.	No.	GM cm.	Low	Med.	High	Low	Med.	High	Low	Med.	High
ZERO SPEED →	7	62.5								2.07	
1. LOW SPEED $Fn = 0.17$	0	-2.0		5.10						5.13	
	1	7.2		5.03			5.07			5.06	
	2	16.4	4.01					5.01		4.05	
	3										
	4	34.8	3.01	2.09 3.09			3.06			3.07	
	5 6										
	7	62.5	2.01			2.05			2.04		
2. MEDIUM SPEED $Fn = 0.25$	0	-2.0		5.12							
	1	7.2		5.04			5.09				
	2	16.4		4.02 4.04			4.06				
	3										
	4	34.8	3.02	2.10 3.08			3.05				
	5 6										
	7	62.5	2.02			1.03				1.07	
3. HIGH SPEED $Fn = 0.30$	0	-7.0		5.11							
	1	7.2		5.05			5.08				
	2	16.4		4.03				5.02			
	3										
	4	34.8	3.03	2.11x 3.10			3.04				
	5 6										
	7	62.5	1.01 2.03			1.02	2.07			1.04	

x - indicates run resulting in model capsizing.

Table II: (cont.)

<u>Heavy</u> Model Displacement Condition

HEADING			FOLLOWING			QUARTERING			BEAM		
Wave Height Cond.			Low	Med.	High	Low	Med.	High	Low	Med.	High
	No.	GM cm.									
1. LOW SPEED $F_n = 0.17$	0 1										
	2	7.8	9.02 13.01	10.01x	8.01x	9.04 13.03x	13.10x	10.04x	13.06		10.03
	3	17.0		11.04x			11.02 12.01x			11.01	
	4	26.2		7.01			7.05			7.08	
	5	35.4	14.01 14.07			14.04			14.08		
	6										
	7	53.8	6.01		8.02	6.05		8.03	6.04		8.04
2. MEDIUM SPEED $F_n = 0.22$	0 1										
	2	7.8	9.03 13.02	9.08	13.11x		9.09x 13.08x 9.10x 13.09x				
	3	17.0			12.03x 12.04x 12.05x			12.02			
	4	26.2		7.02			7.06				
	5	35.4	14.02 14.09			14.05					
	6										
	7	53.8	6.02		8.05	6.06		8.06			

Table II: (cont.)

HEADING			FOLLOWING			QUARTERING			HEAD		
Wave Height Cond.			Low	Med.	High	Low	Med.	High	Low	Med.	High
	GM No.	GM Cm.									
3. HIGH SPEED $F_n = 0.26$	0 1										
	2	7.8	13.04 13.05	9.06		13.07x	9.07		9.05		10.02
	3	17.0		11.03	12.07x			12.06x 12.08x			
	4	26.2		7.03x 7.04			7.07				
	5	35.4	14.03 14.10			14.06			14.11		
	6										
	7	53.8	6.03		8.07	6.07		8.08			8.09

x - indicates run resulting in model capsizing.

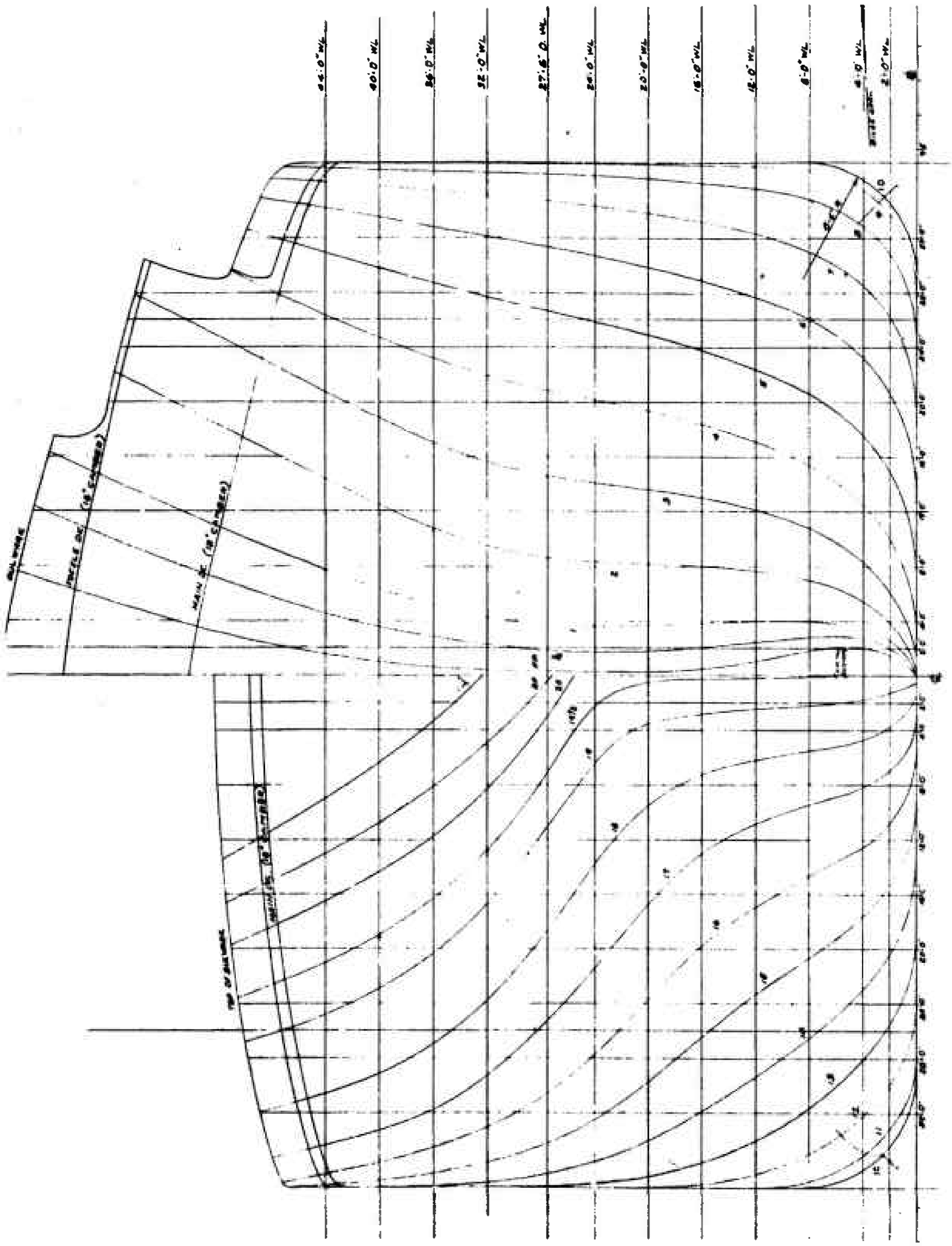


Figure 1. Body Plan of American Challenger

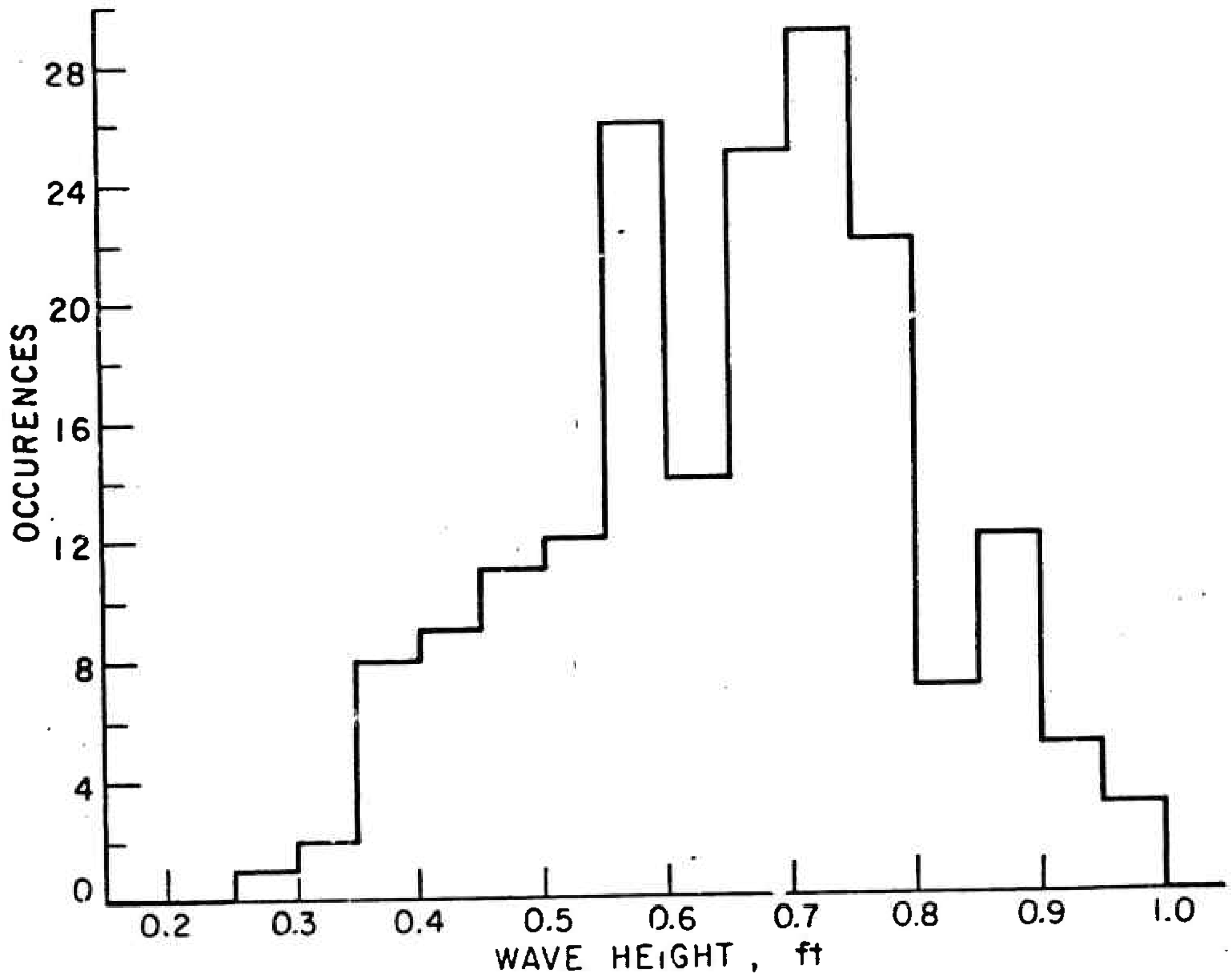


FIG. 2 HISTOGRAM OF SIGNIFICANT HEIGHTS OF WAVE RECORDS MEASURED DURING 1971 TESTING SEASON

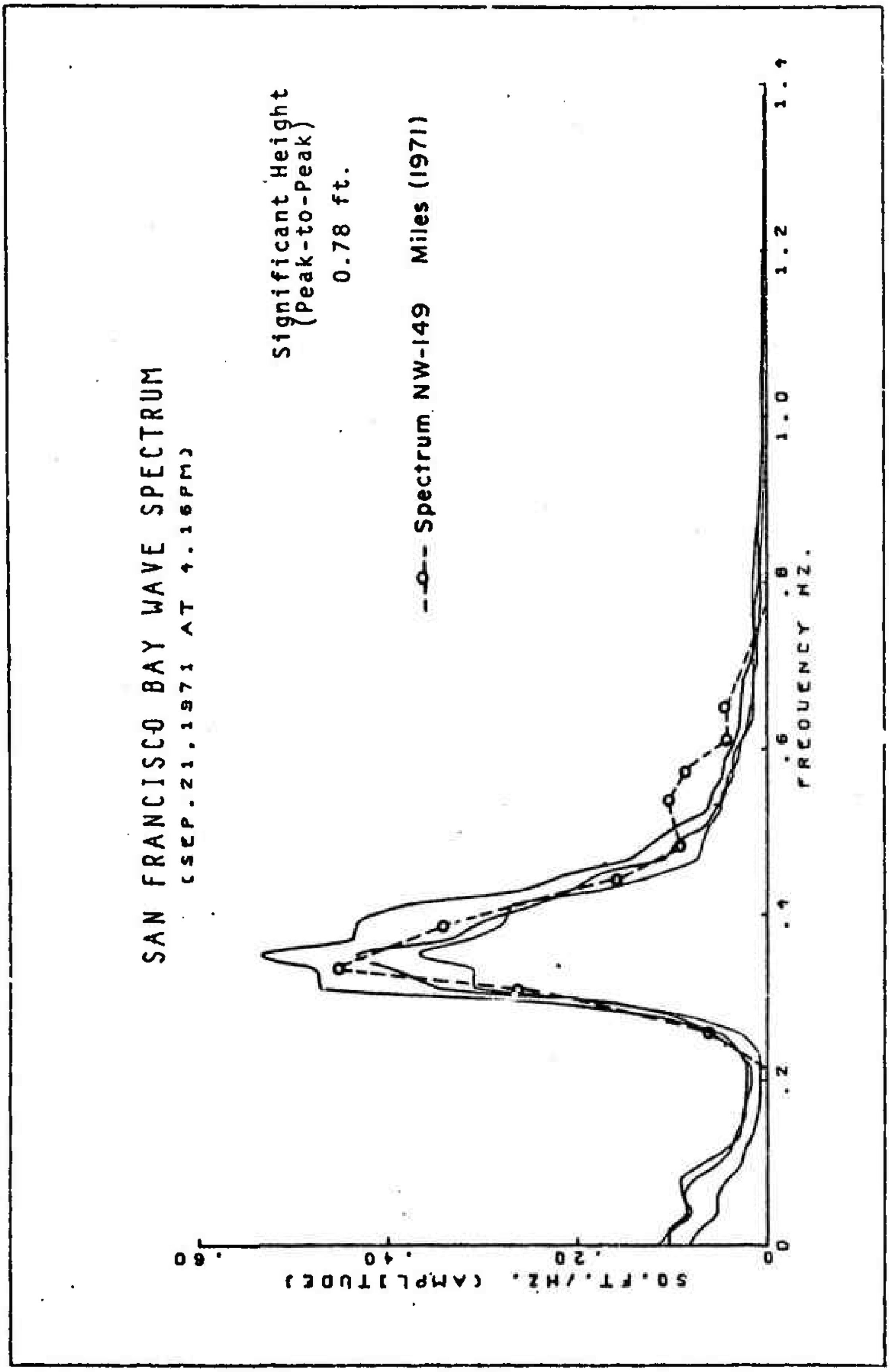
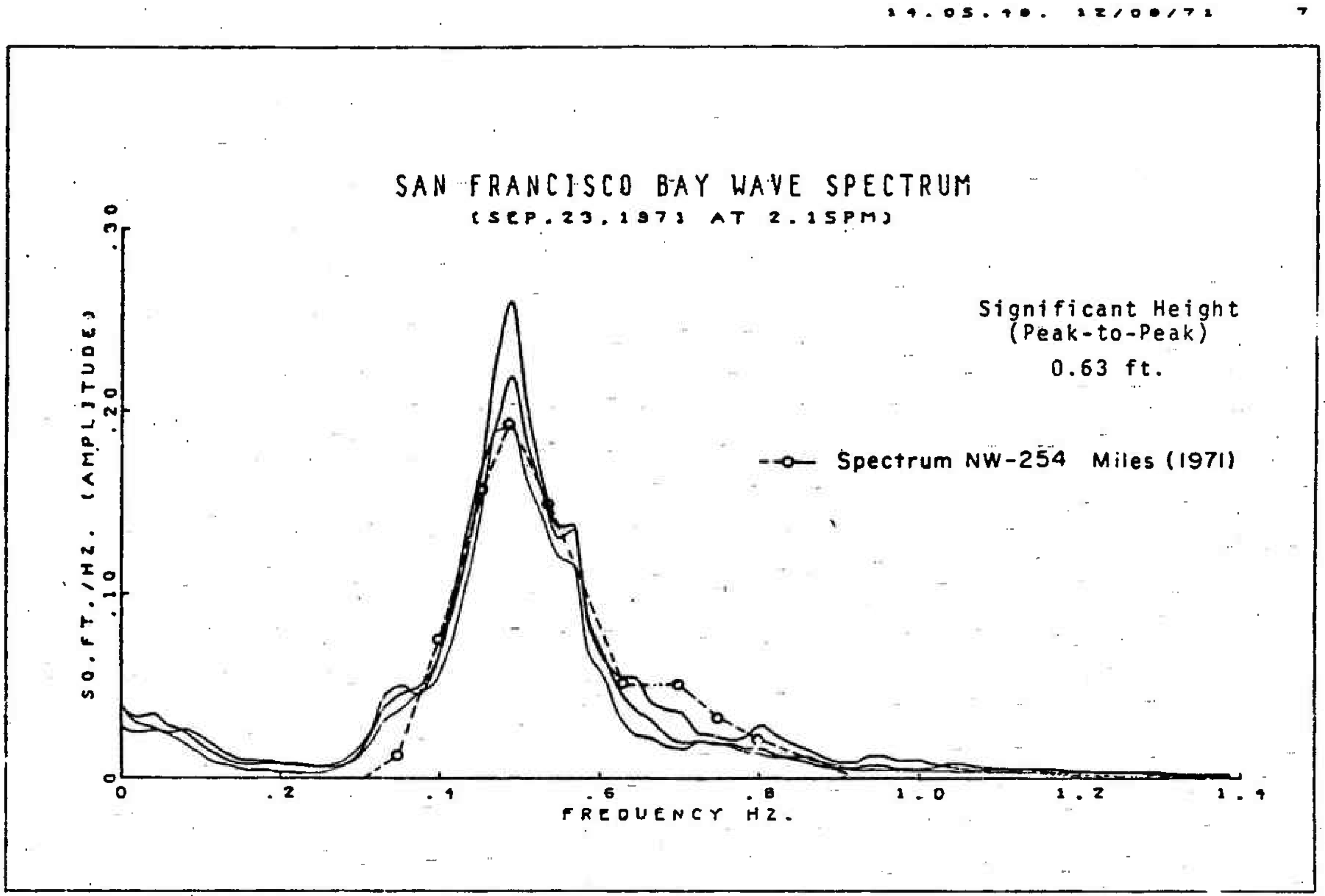

14.05.48. 12/08/71
SAN FRANCISCO BAY WAVE SPECTRUM
(SEP.21.1971 AT 4.15PM)
Significant Height (Peak-to-Peak)
0.78 ft.
Spectrum NW-149
Miles (1971)
SQ.FT./HZ. (AMPLITUDE)
0
.20
.40
.60
.2
.4
.6
.8
1.0
1.2
1.4
FREQUENCY HZ.

Figure 3


14.05.40. 12/08/71 7
SAN FRANCISCO BAY WAVE SPECTRUM
(SEP.23,1971 AT 2.15PM)
Significant Height
(Peak-to-Peak)
0.63 ft.
Spectrum NW-254 Miles (1971)
SQ.FT./HZ. (AMPLITUDE)
FREQUENCY HZ.
0
.10
.20
.30
.2
.4
.6
.8
1.0
1.2
1.4

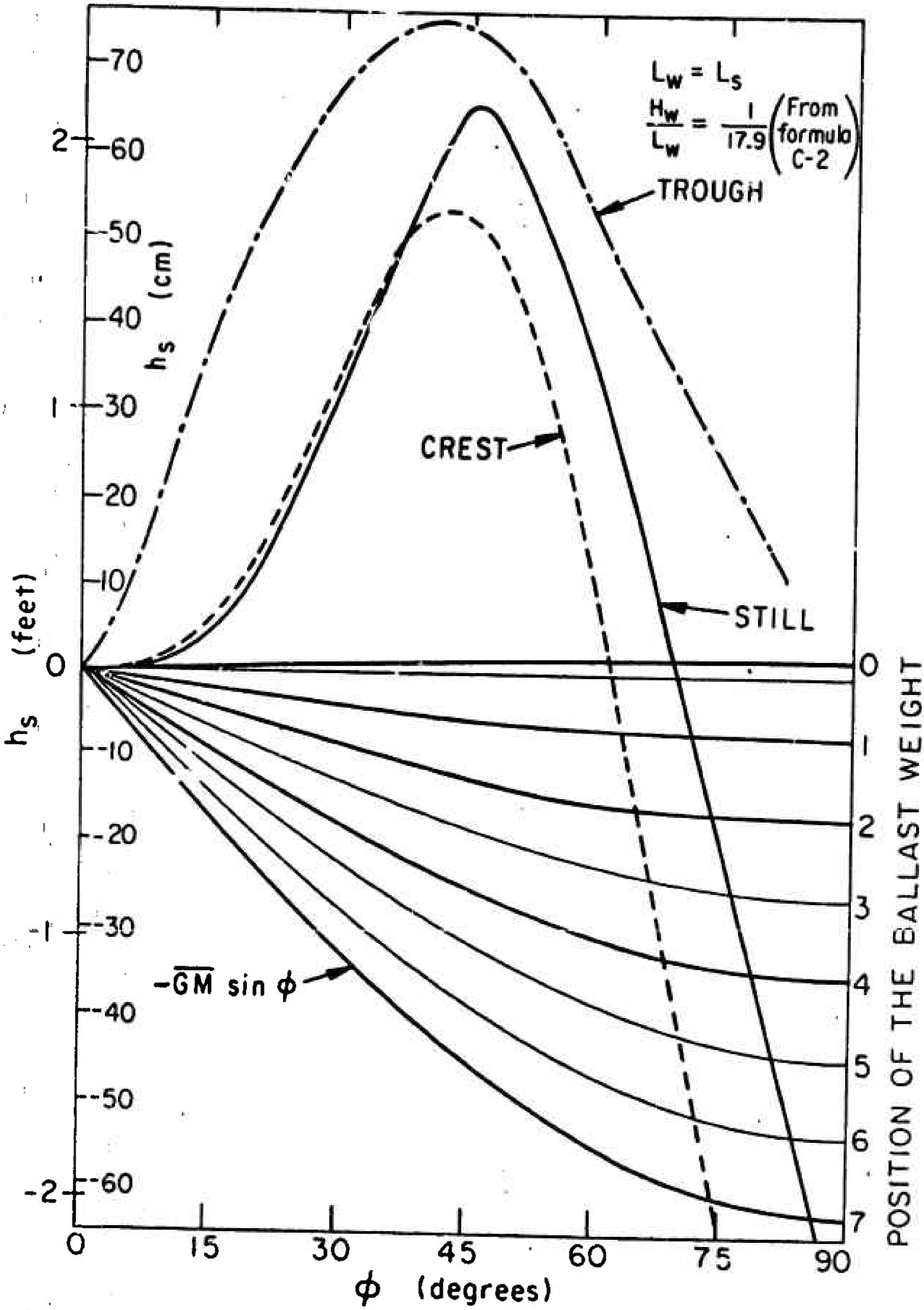


Figure 5. RIGHTING ARM CURVES, SHIP "CHALLENGER" FOR LIGHT MODEL CONDITION

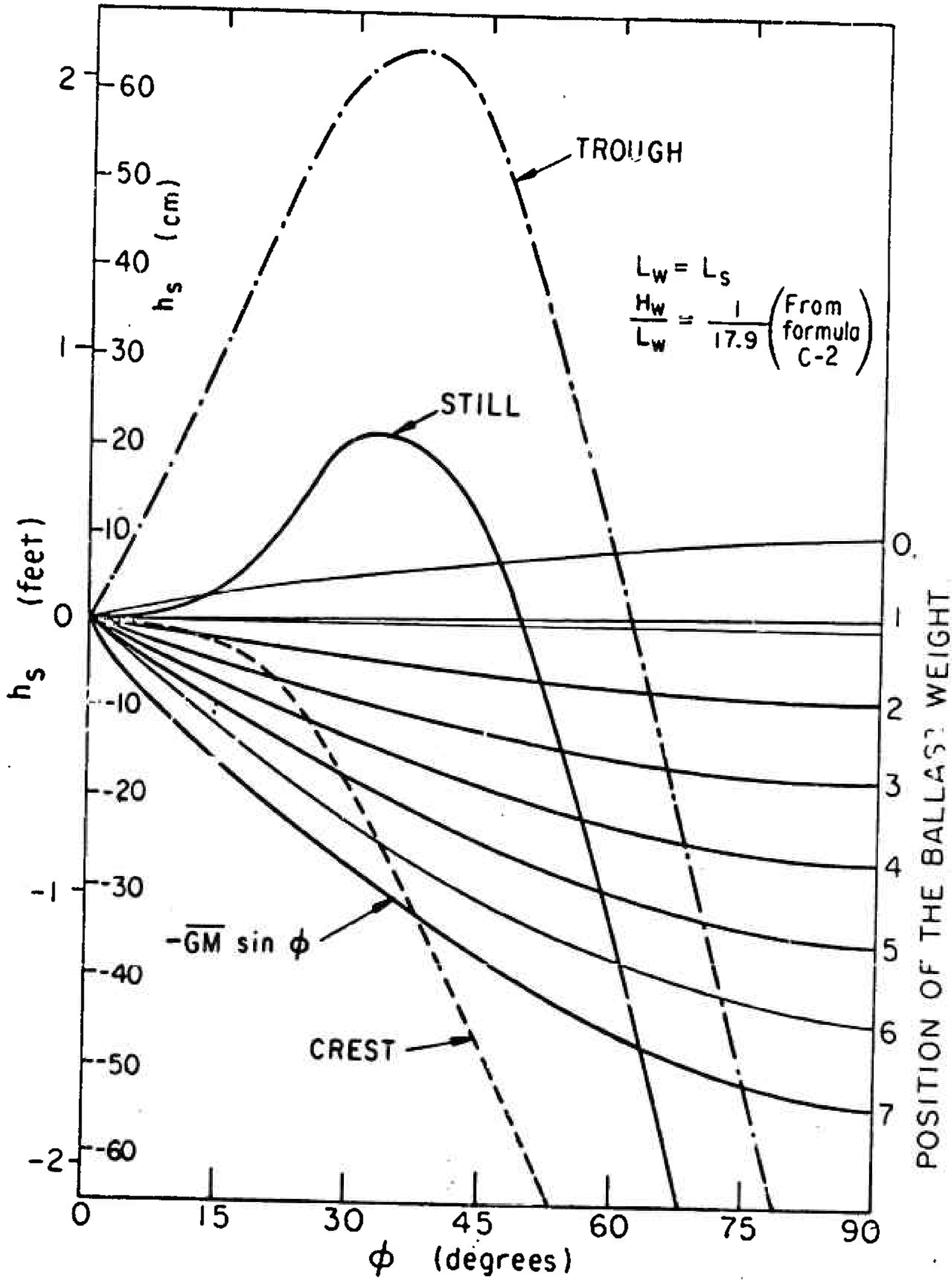


Figure 6. **RIGHTING ARM CURVES, SHIP "CHALLENGER" FOR HEAVY MODEL CONDITION**

N A GRAPH 3.0 18.00.01. 08/03/72 1

NORMALIZED ROLL, PITCH AND SEA SPECTRA

RUN 2.11 ON 3 AUG. 1971 AT 3.15

Capsizing after 395.3 sec., Following Sea, F_n=.30, GM_4= 0.0152B=34.8 cm

Spectral Area m_o	Roll Degr.^{2}	Pitch Degr.^{2}	Seaway1, ft.^{2} at 1:05 p.m.	Seaway2, ft.^{2} at 2:40 p.m.
	213.99	4.42	0.064	0.111
Seq. No.	14	14	2	3

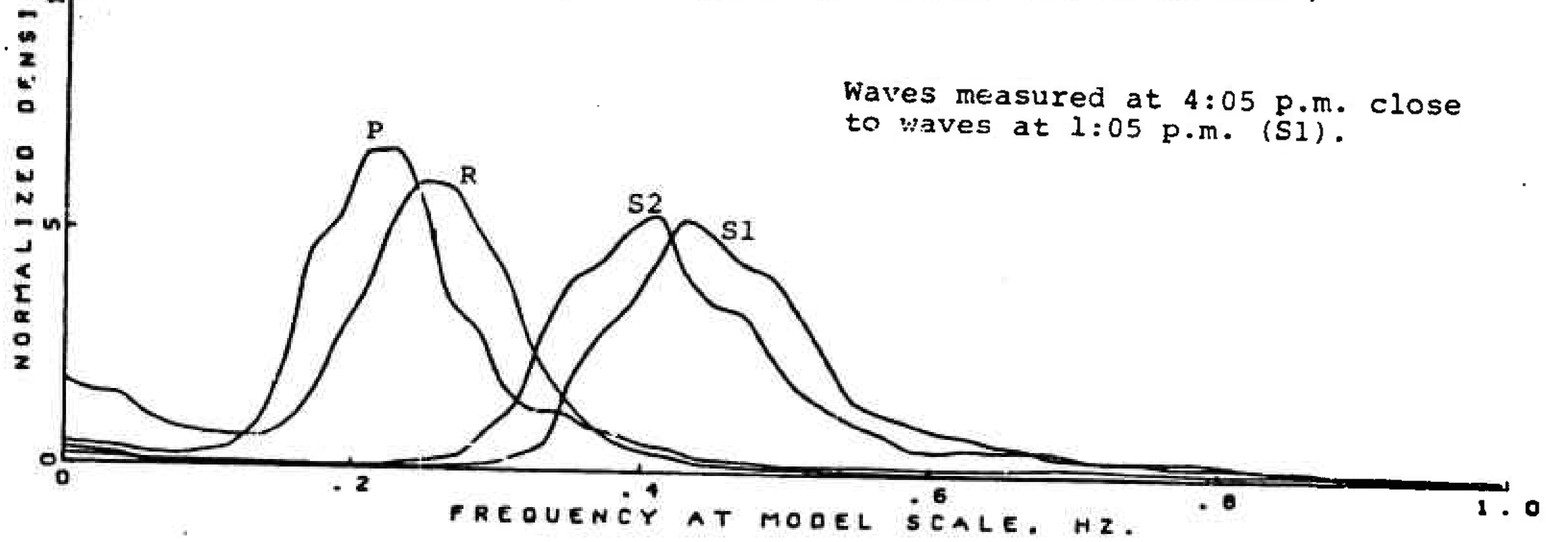


Figure 7

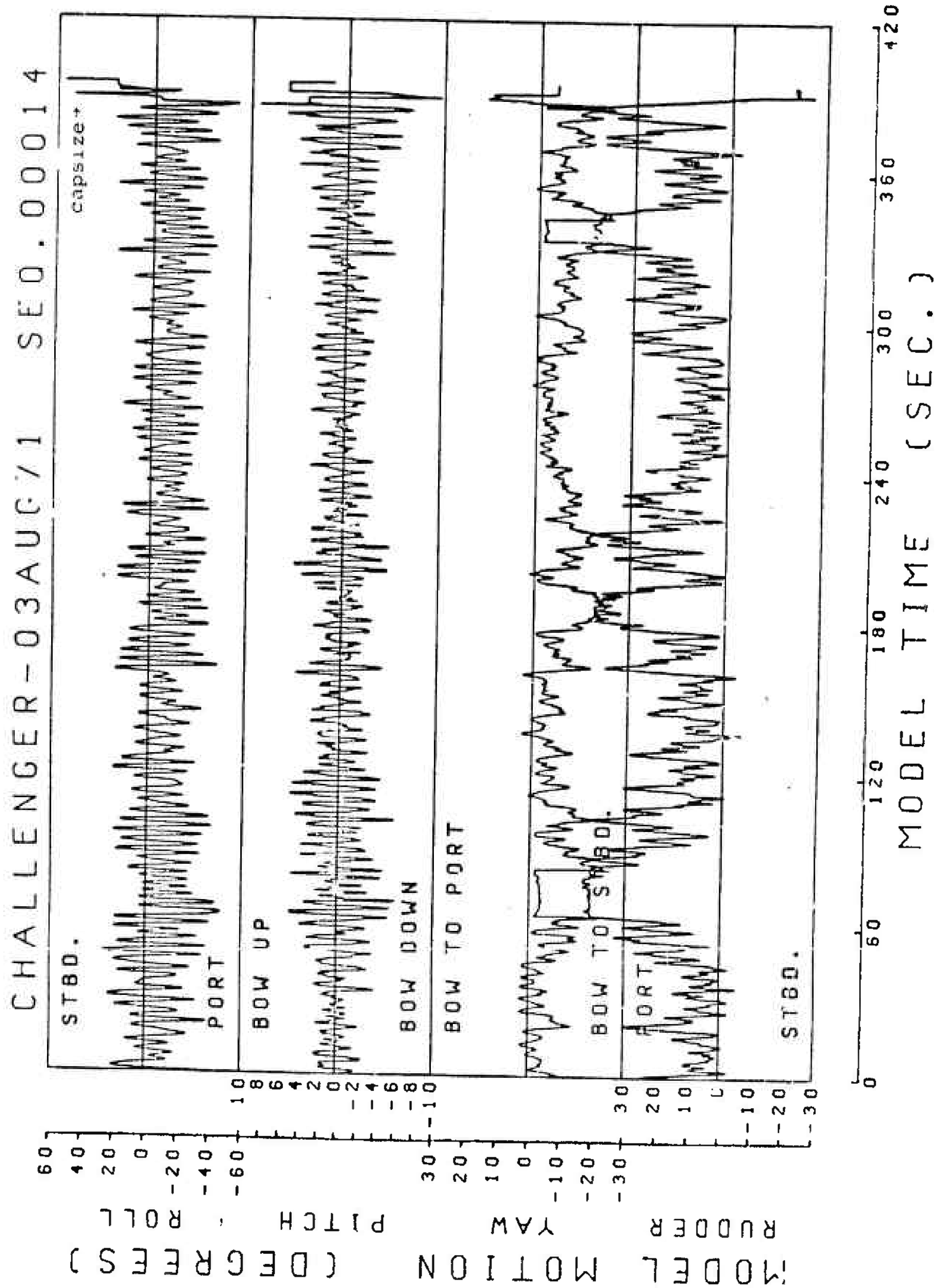

CHALLENGER-03AUG71 SEQ.00014
capsize
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
MODEL MOTION (DEGREES)
ROLL
PITCH
YAW
RUDDER
MODEL TIME (SEC.)
0
60
120
180
240
300
360
420

Figure 8

N A GRAPH 3.0 10.00.01. 08/03/72 2

NORMALIZED ROLL, PITCH AND SEA SPECTRA

RUN 3.10 ON 5 AUG. 1871

at 3:05 p.m.

No Capsizing in 7 min., Following Sea, F_n=.30, GM_4= 0.0152B=34.8 cm

Spectral Area m_o	Roll Degr.^{2}	Pitch Degr.^{2}	Seaway1, ft.^{2} at 11:05 a.m.	Seaway2, ft.^{2} at 1:10 p.m.
	289.02	3.88	0.022	0.084
Seq. No.	12	12	1	2

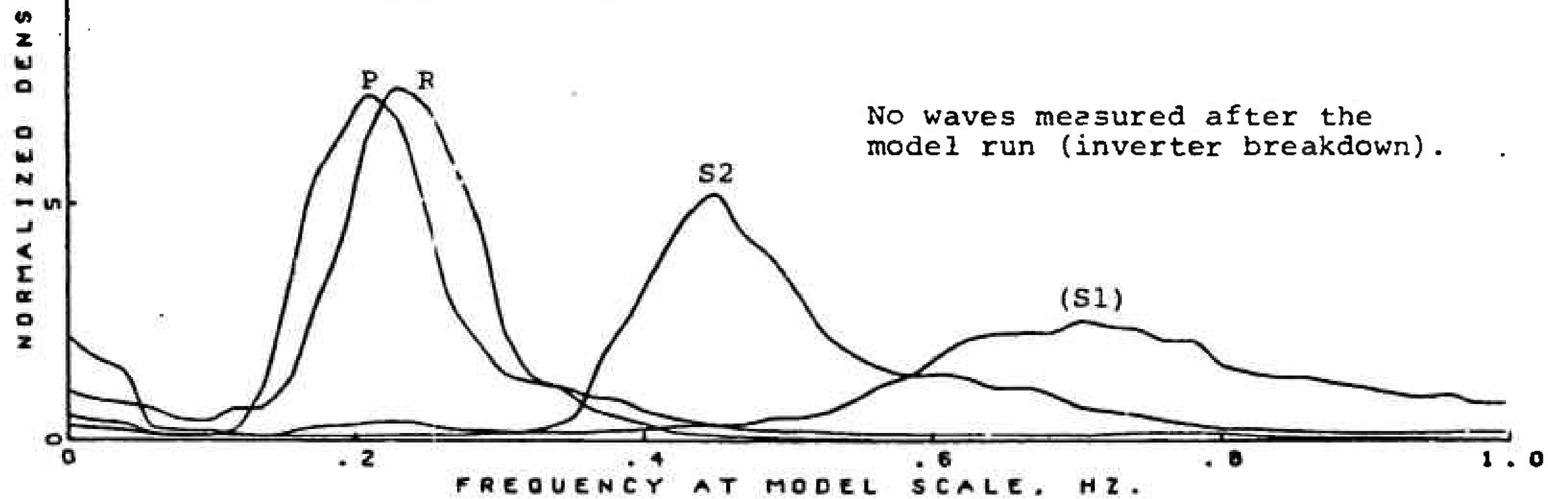
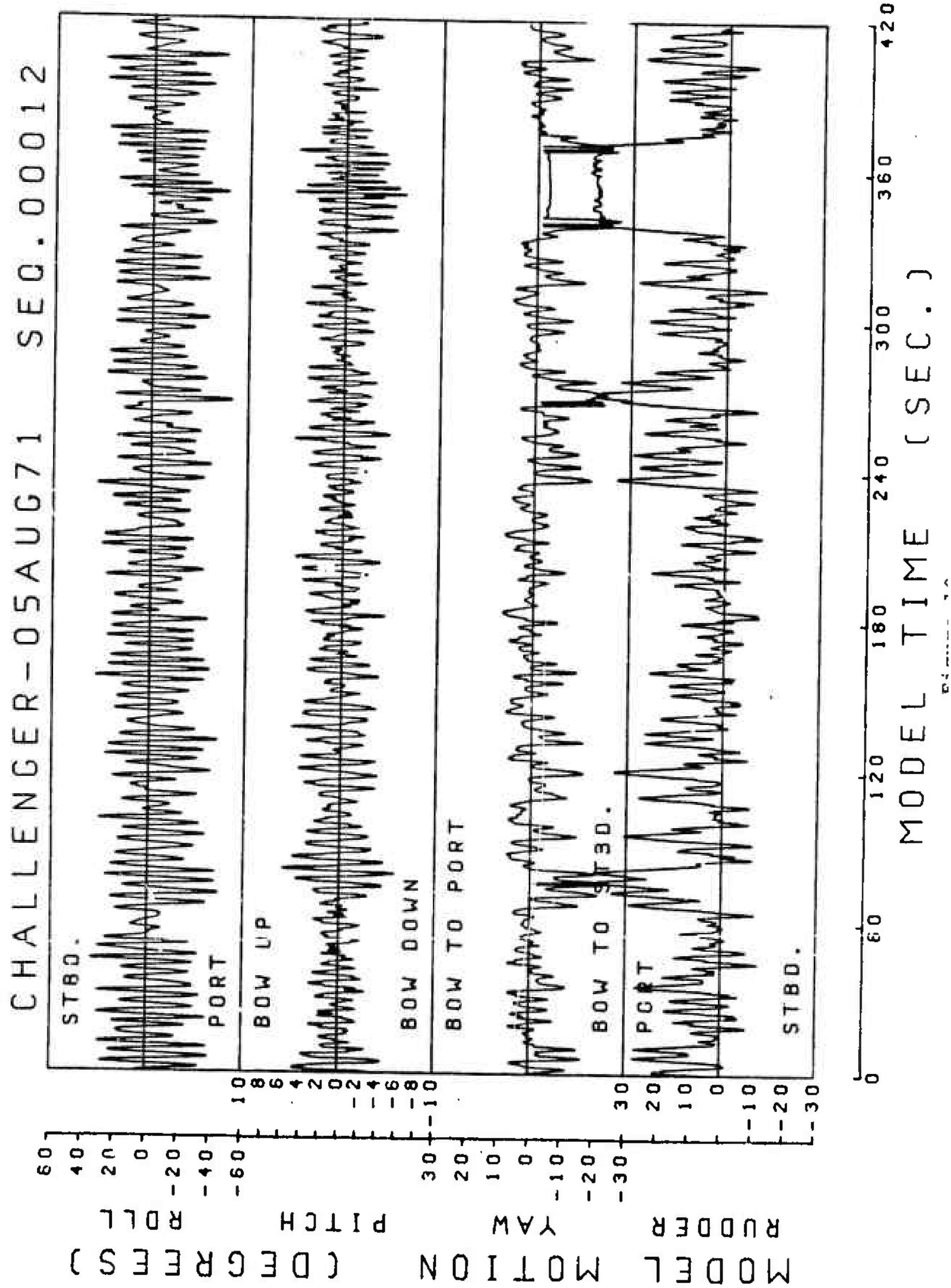
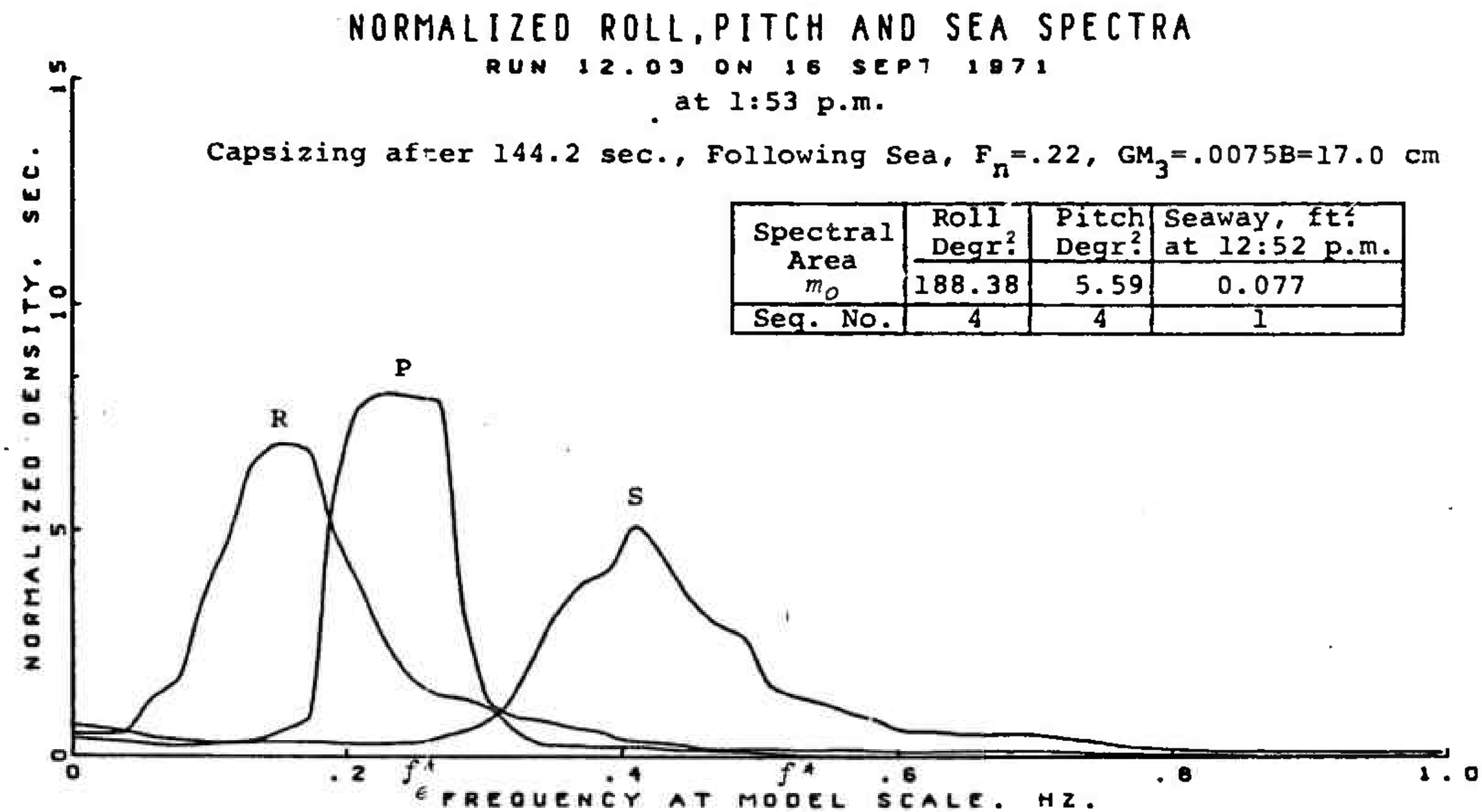


Figure 9

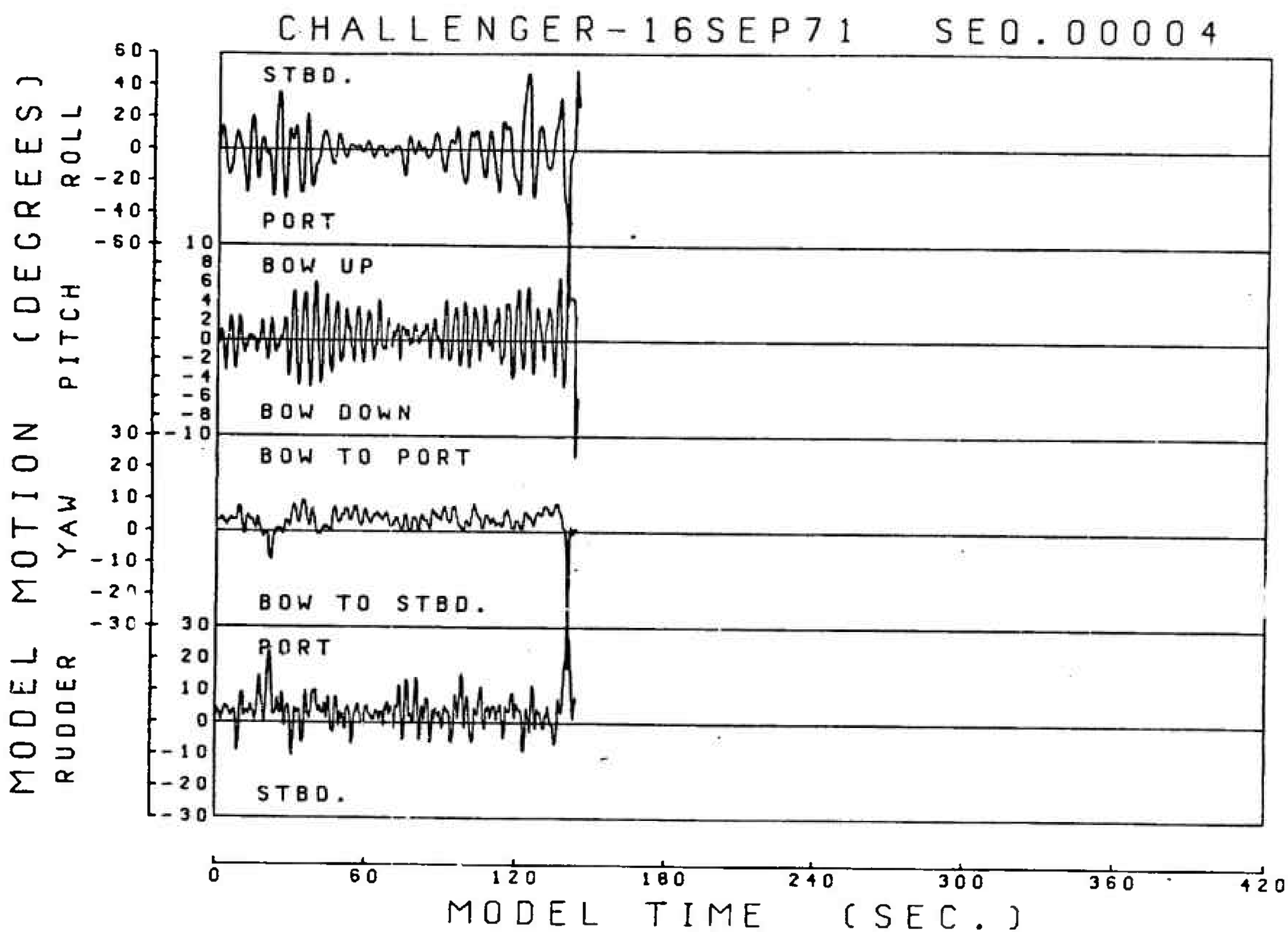

CHALLENGER-05AUG71 SEQ.00012
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
MODEL MOTION (DEGREES)
ROLL
PITCH
YAW
RUDDER
MODEL TIME (SEC.)
0
60
120
180
240
300
360
420

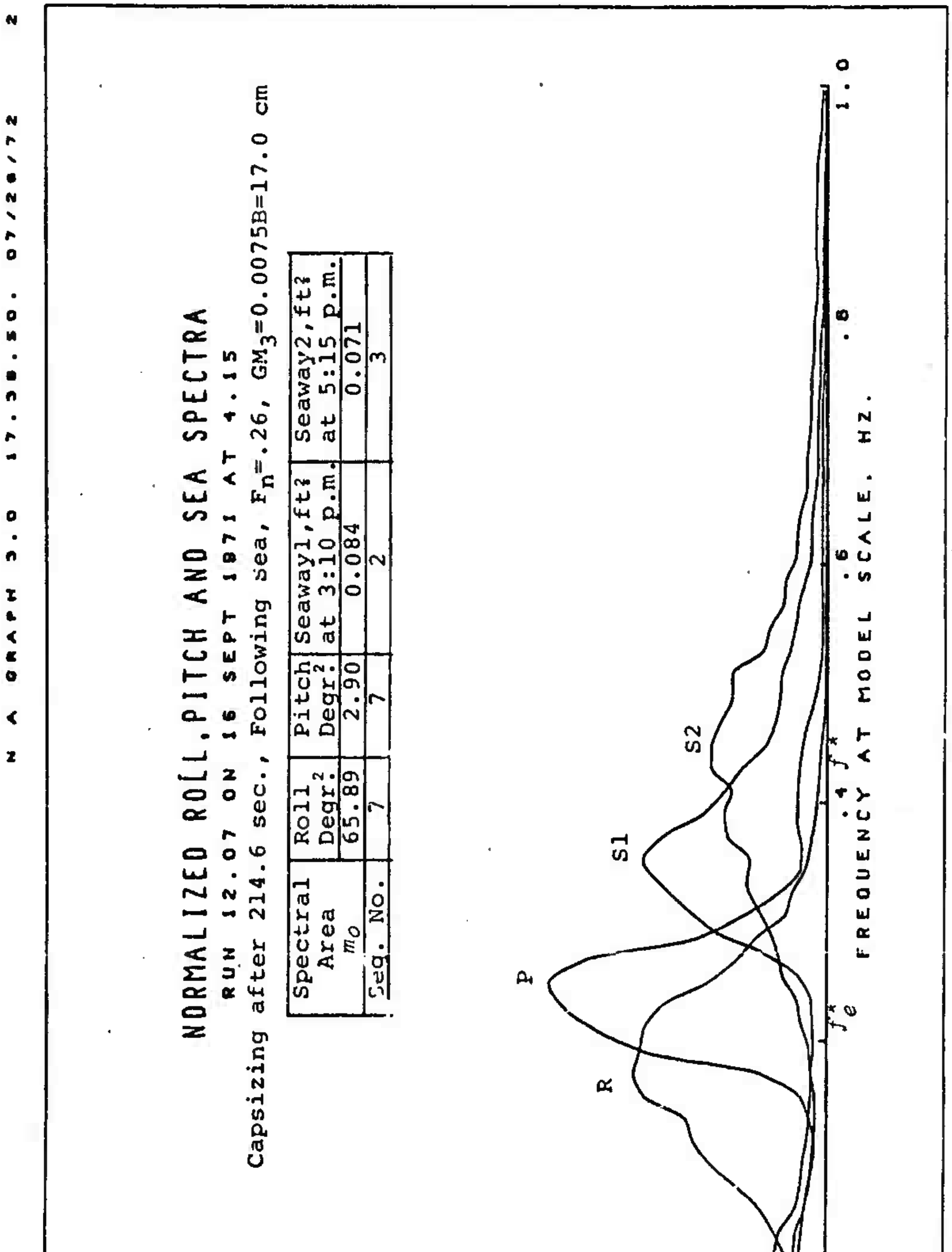
N A GRAPH 3.0 12.58.17. 07/14/72 2



Spectral Area m_0	Roll Degr.²	Pitch Degr.²	Seaway, ft.² at 12:52 p.m.
	188.38	5.59	0.077
Seq. No.	4	4	1

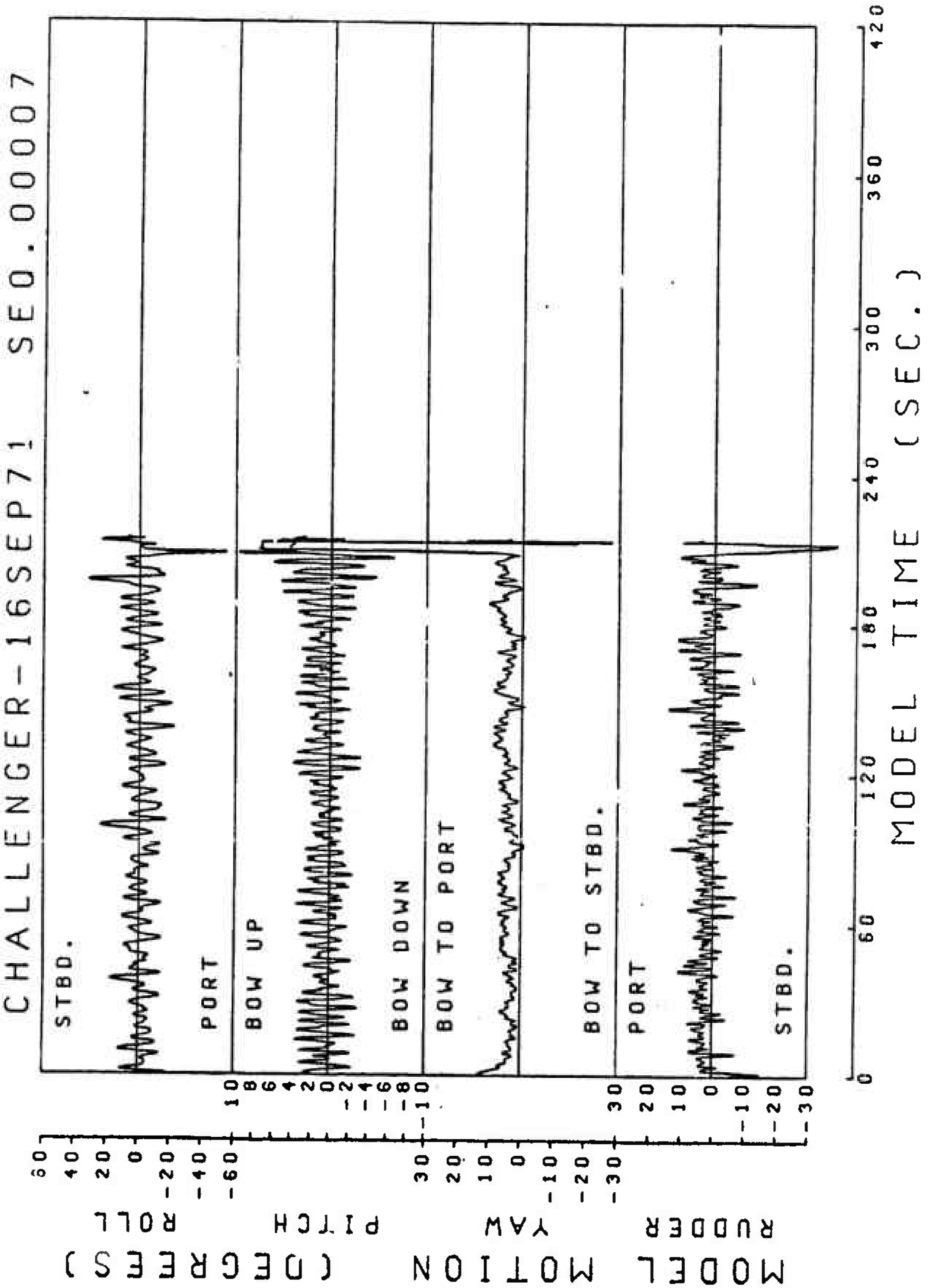
Figure 11


CHALLENGER-16SEP71 SEQ.00004
MODEL MOTION (DEGREES)
ROLL
PITCH
YAW
RUDDER
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
60
40
20
0
-20
-40
-60
10
8
6
4
2
0
-2
-4
-6
-8
-10
30
20
10
0
-10
-30
30
20
10
0
-10
-20
-30
0
60
120
180
240
300
360
420
MODEL TIME (SEC.)



Spectral Area m_o	Roll Degr.²	Pitch Degr.²	Seaway1, ft² at 3:10 p.m.	Seaway2, ft² at 5:15 p.m.
	65.89	2.90	0.084	0.071
Seq. No.	7	7	2	3

Figure 13


CHALLENGER-16SEP71 SEQ.00007
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
ROLL
PITCH
YAW
RUDDER
MODEL MOTION (DEGREES)
60 40 20 0 -20 -40 -60
10 8 6 4 2 0 -2 -4 -6 -8 -10
30 20 10 0 -10 -20 -30
30 20 10 0 -10 -20 -30
0 60 120 180 240 300 360 420
MODEL TIME (SEC.)

N A GRAPH 3.0 17.38.50. 07/28/72 3

NORMALIZED ROLL, PITCH AND SEA SPECTRA

RUN 12.08 ON 16 SEPT 1971 AT 4.32

Capsizing after 348.4 sec., Quartering Sea, F_n=.26, $\bar{G}M_3$=0.0075B=17.0 cm

Spectral Area m_o	Roll Degr.^{2}	Pitch Degr.^{2}	Seaway1, ft.^{2} at 3:10 p.m.	Seaway2, ft.^{2} at 5:15 p.m.
	170.49	5.42	0.084	0.071
Seq. No.	8	8	2	3

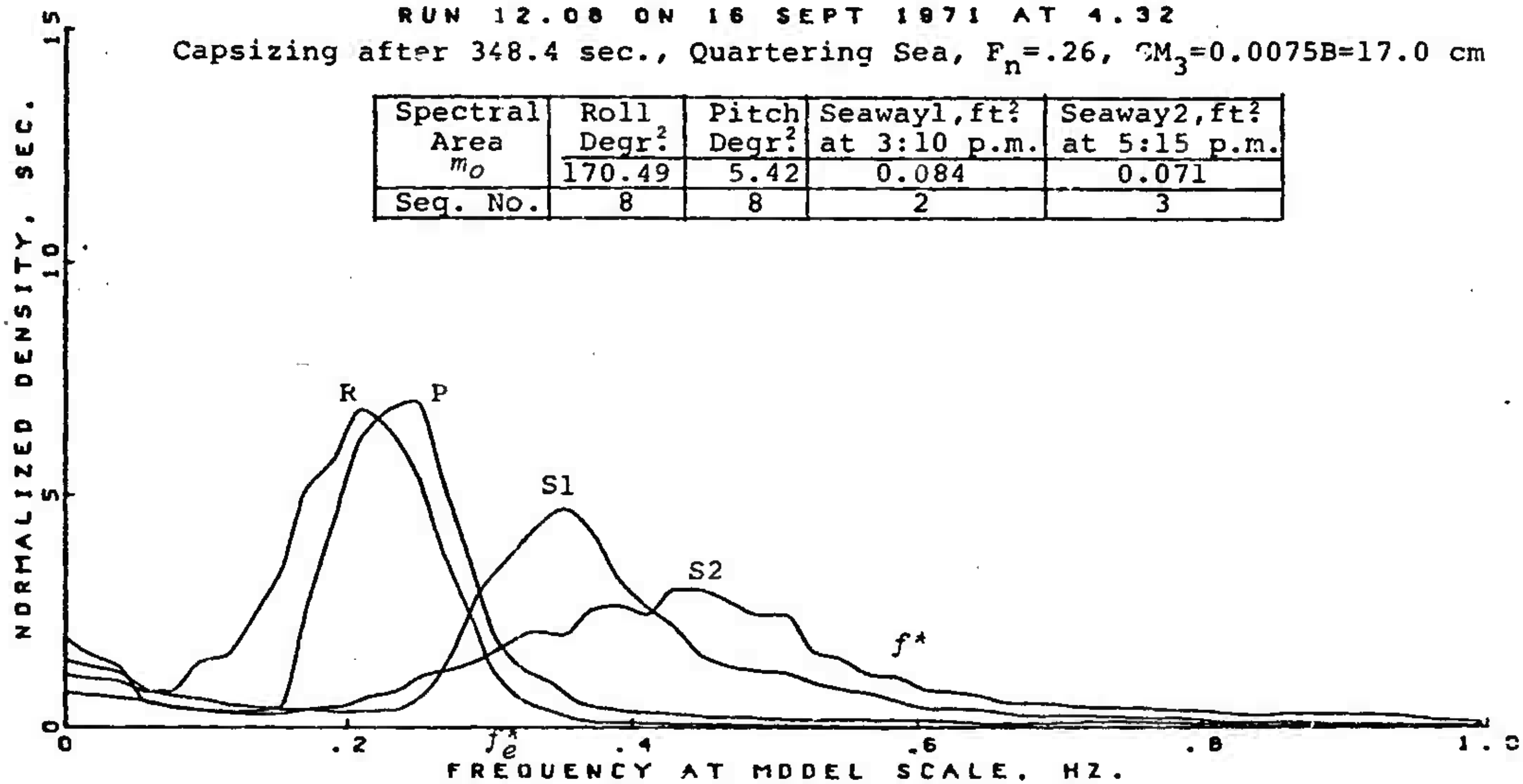
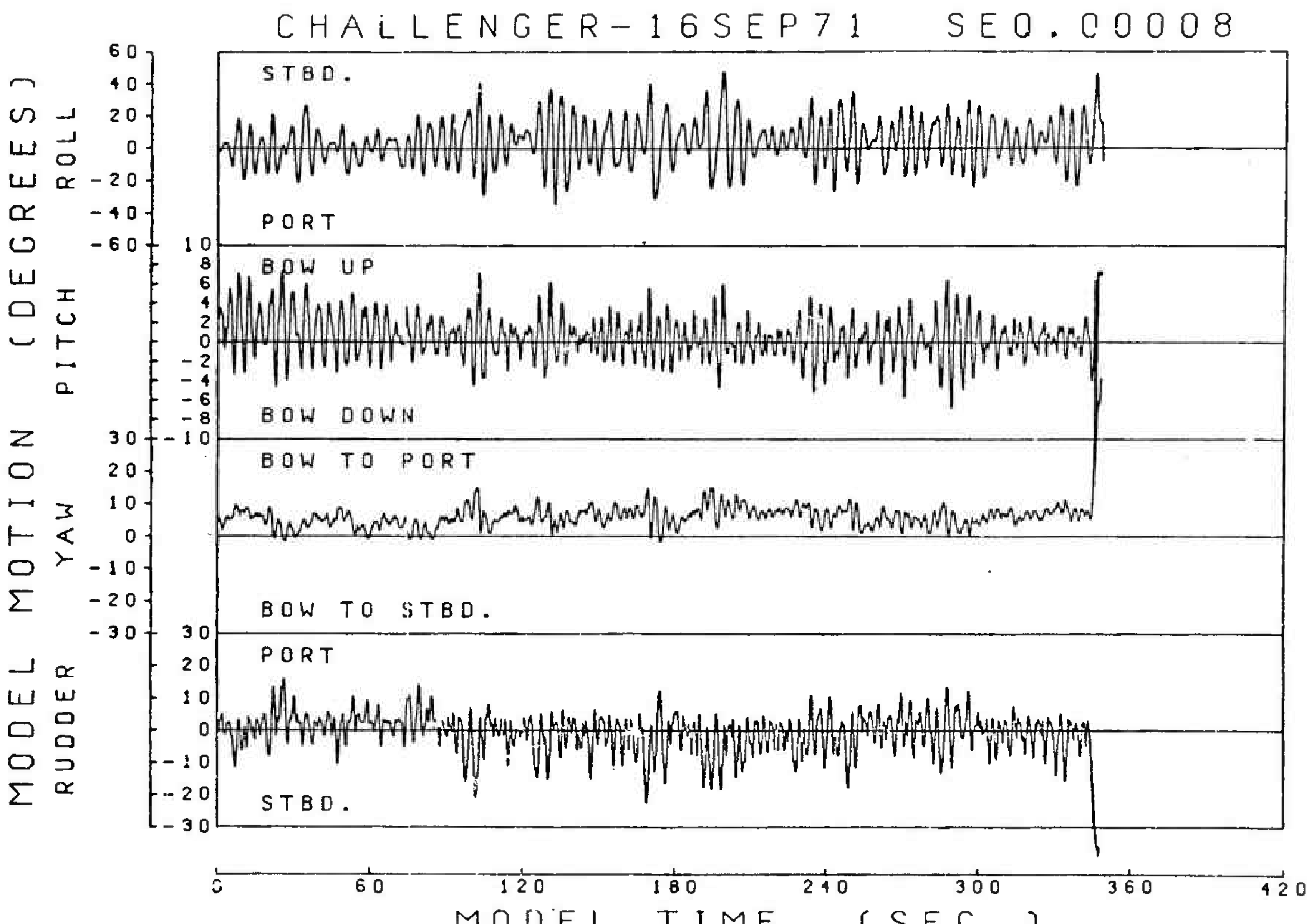


Figure 15



CHALLENGER-16SEP71 SEQ.C0008
MODEL MOTION (DEGREES)
ROLL
PITCH
YAW
RUDDER
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
60
40
20
0
-20
-40
-60
10
8
6
4
2
0
-2
-4
-6
-8
-10
30
20
10
0
-10
-20
-30
30
20
10
0
-10
-20
-30
0
60
120
180
240
300
360
420
MODEL TIME (SEC.)

Figure 16

N A GRAPH 3.0 17.38.50. 07/28/72 8

NORMALIZED ROLL, PITCH AND SEA SPECTRA

RUN 15.04 ON 28 SEPT 1971 AT 12.00, 10° Port List

Capsizing after 119.3 sec., Following Sea, F_n= 26, GM_4=0.0115B=26.2 cm

Spectral Area m_o	Roll Degr.^{2}	Pitch Degr.^{2}	Seaway1, ft.^{2} at 11:22 a.m.	Seaway2, ft.^{2} at 1:19 p.m.
	93.07	1.76	0.045	0.097
Seq. No.	5	5	1	4

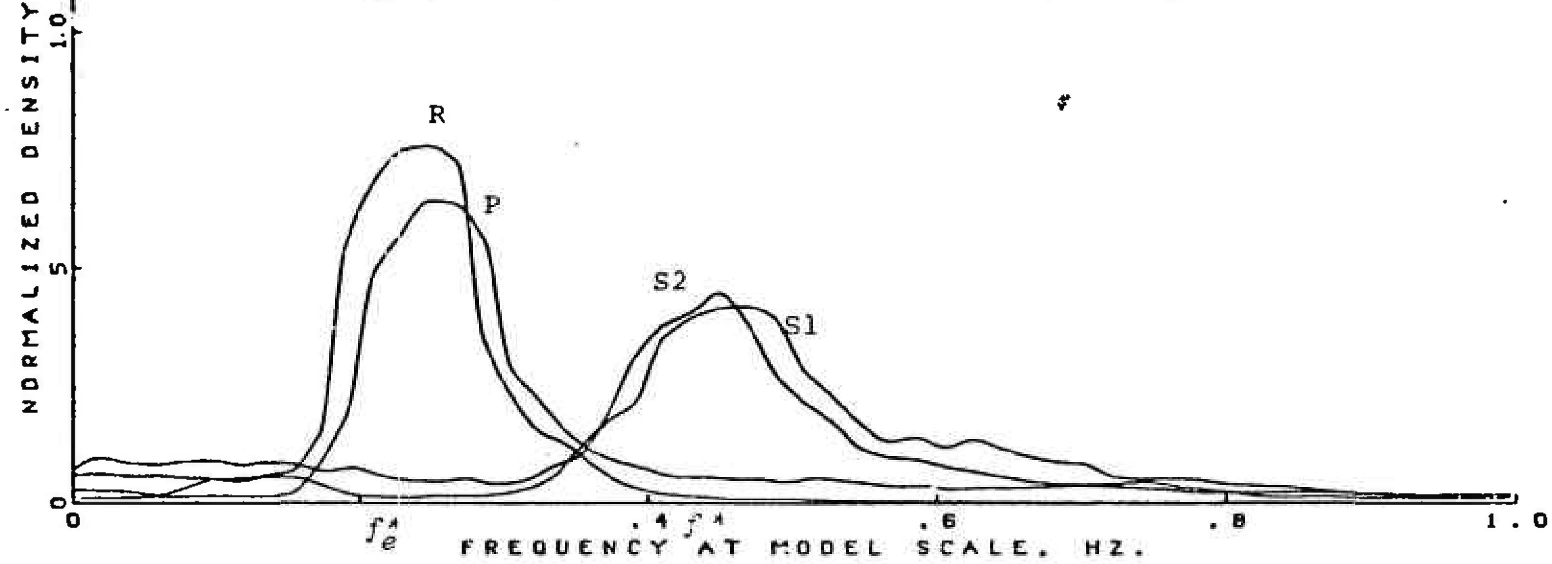
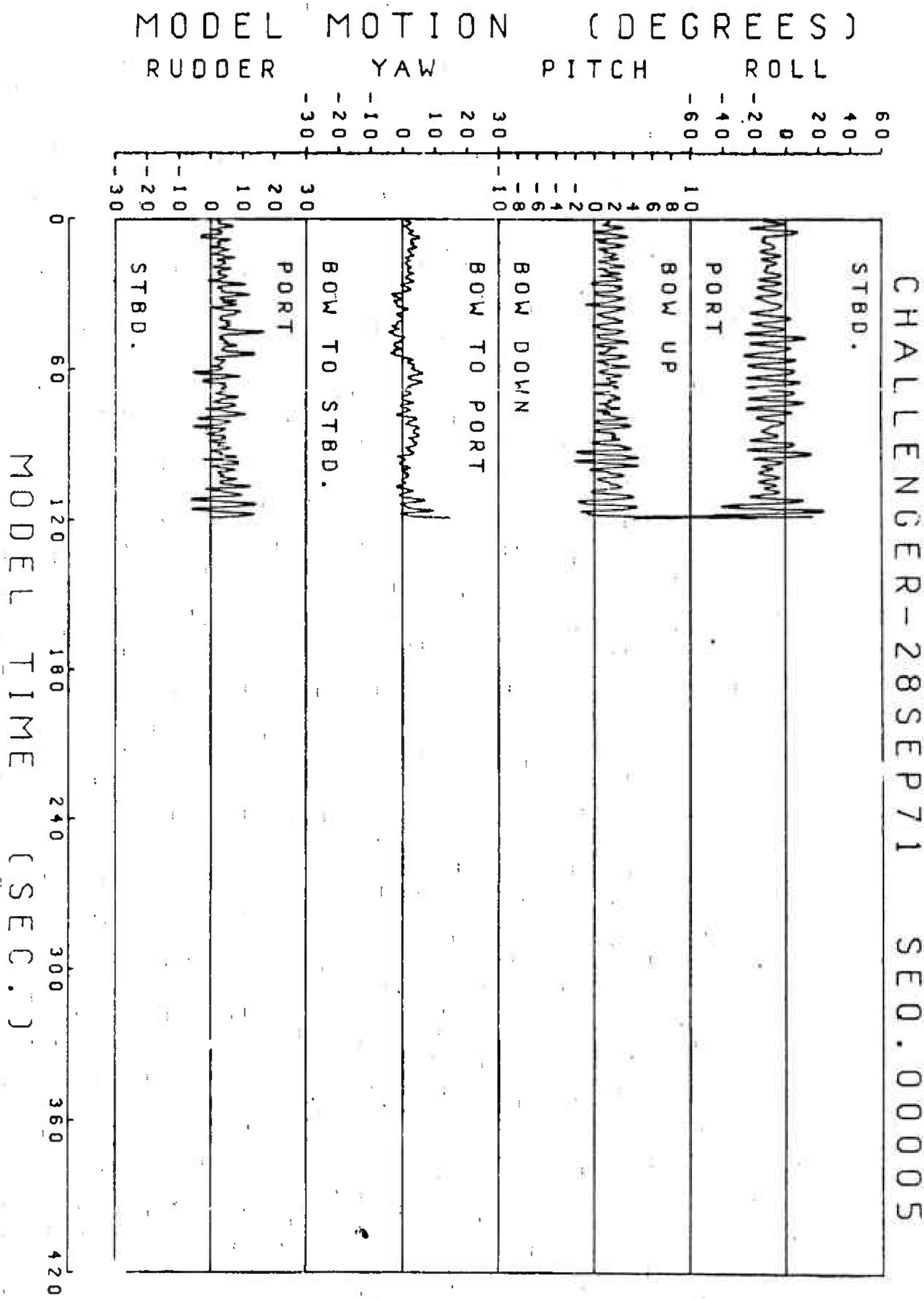


Figure 17


MODEL MOTION (DEGREES)
RUDDER
YAW
PITCH
ROLL
CHALLENGER-28SEP71 SEQ.00005
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
MODEL TIME (SEC.)
0
60
120
180
240
300
360
420

N A GRAPH 3.0 17.38.50. 07/28/72

NORMALIZED ROLL, PITCH AND SEA SPECTRA

RUN 15.05 ON 28 SEPT 1971 AT 12.25, 10° Port List

No Capsizing in 7 min., Following Sea, F_n=.26, GM_4=0.0115B=26.2 cm

Spectral Area	Roll Degr.^{2}	Pitch Degr.^{2}	Seaway1, ft.^{2} at 11:22 p.m.	Seaway2, ft.^{2} at 1:19 p.m.
m_o	128.00	2.50	0.045	0.097
Seq. No.	6	6	1	4

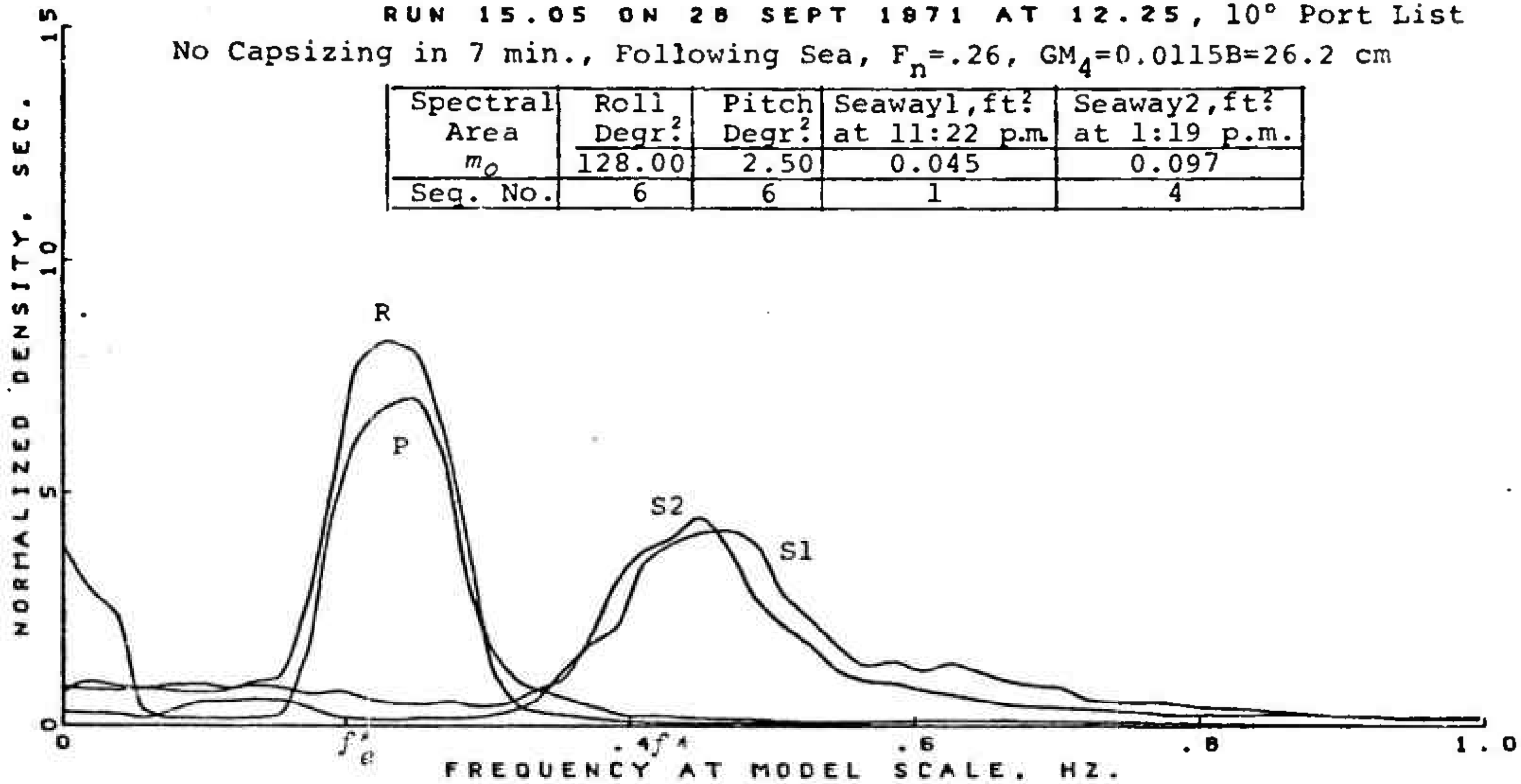


Figure 19

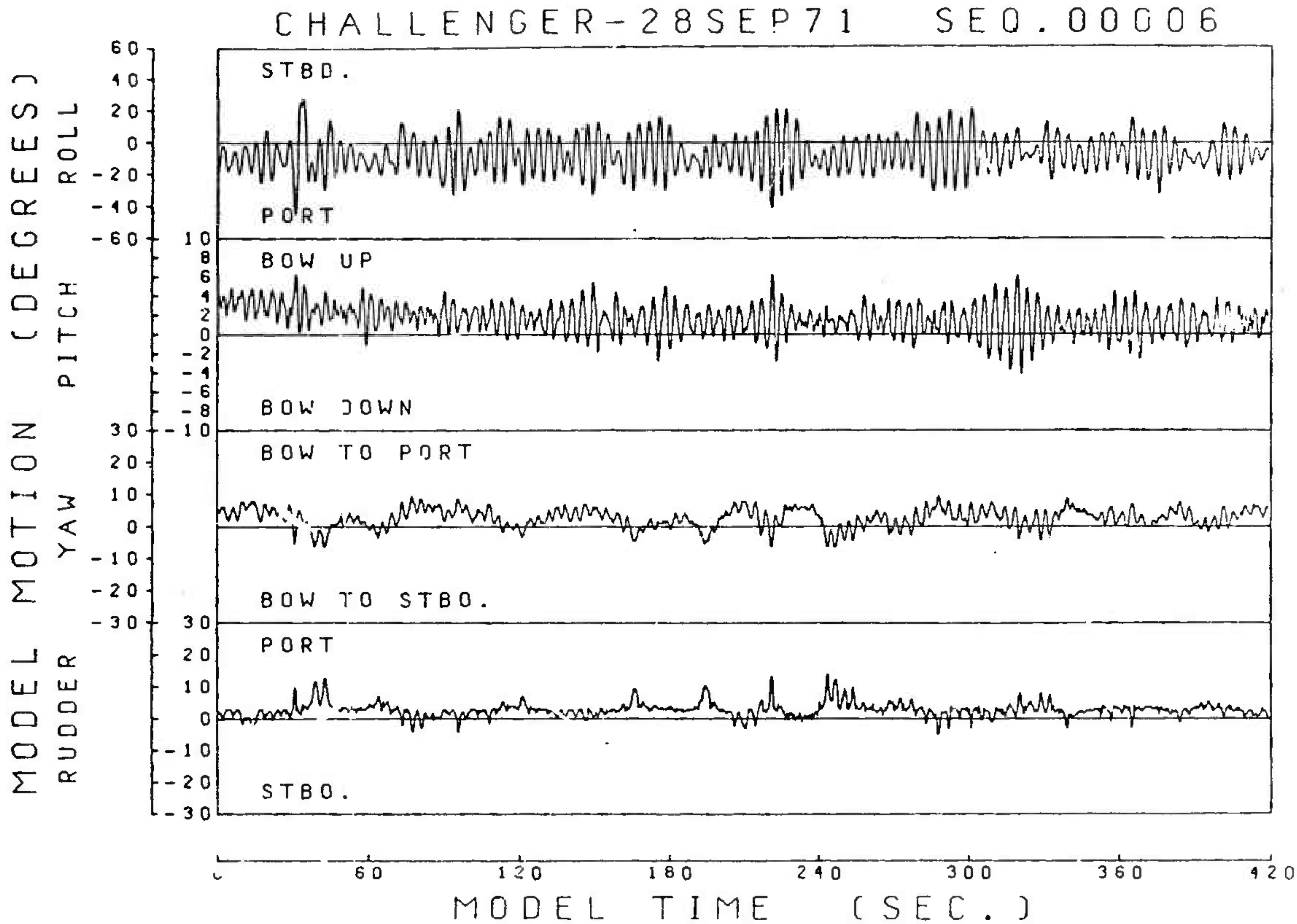

CHALLENGER-28SEP71 SEQ.00006
MODEL MOTION (DEGREES)
ROLL
PITCH
YAW
RUDDER
STBD.
PORT
BOW UP
BOW DOWN
BOW TO PORT
BOW TO STBD.
PORT
STBD.
MODEL TIME (SEC.)

Figure 20